

# SOLAR ENERGY

## JOURNAL OF SOLAR ENERGY SCIENCE AND ENGINEERING

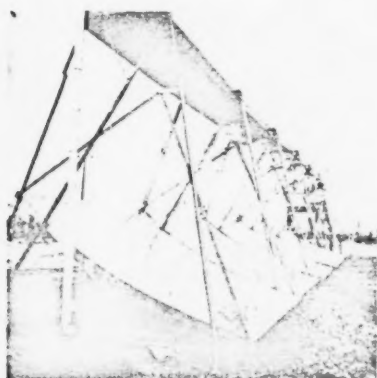
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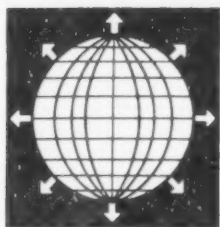
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The cover photo for this issue shows the solar steam boiler, designed for steam at 100 psi, which was exhibited at the opening of the Negev Desert Research Institute in Beersheba, Israel, on October 30, 1957. The inaugural lecture given at this meeting by H. Tabor of the National Physical Laboratory of Israel will be found on page 3.

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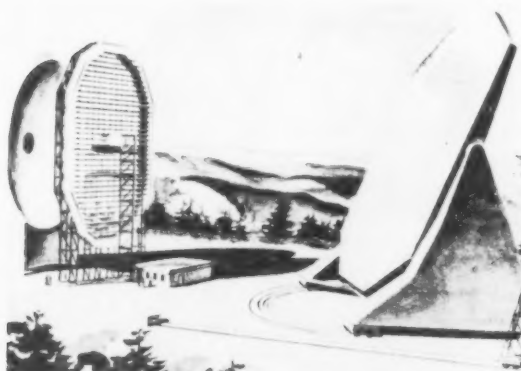
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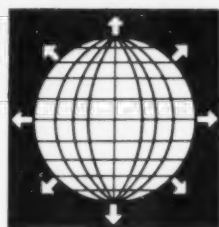
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The cover for this issue shows an artist's sketch of the giant solar furnace which will be built for the Air Force near Holloman Air Force Base, N.M. The furnace, developed jointly by J. W. Fecker, Inc., and Pittsburgh-Des Moines Steel, will consist of a 145-ft square, 1½ million-lb heliostat (left) and a 108-ft diameter parabolic mirror (right). This latter will focus the sun's rays onto a 5-in. diameter spot in the laboratory unit in front of the venetian-blind-like shutter. Temperatures of 7,000°C are expected.

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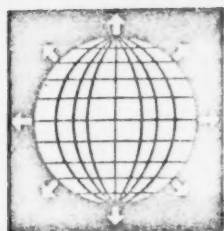
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Cover photo of the sun by Stuart Weiner, Phoenix.

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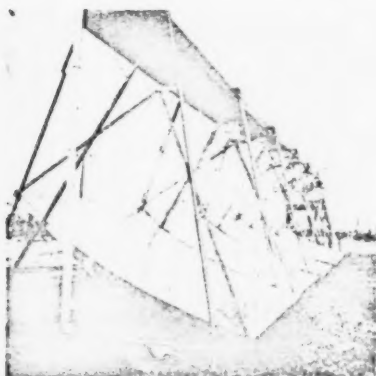
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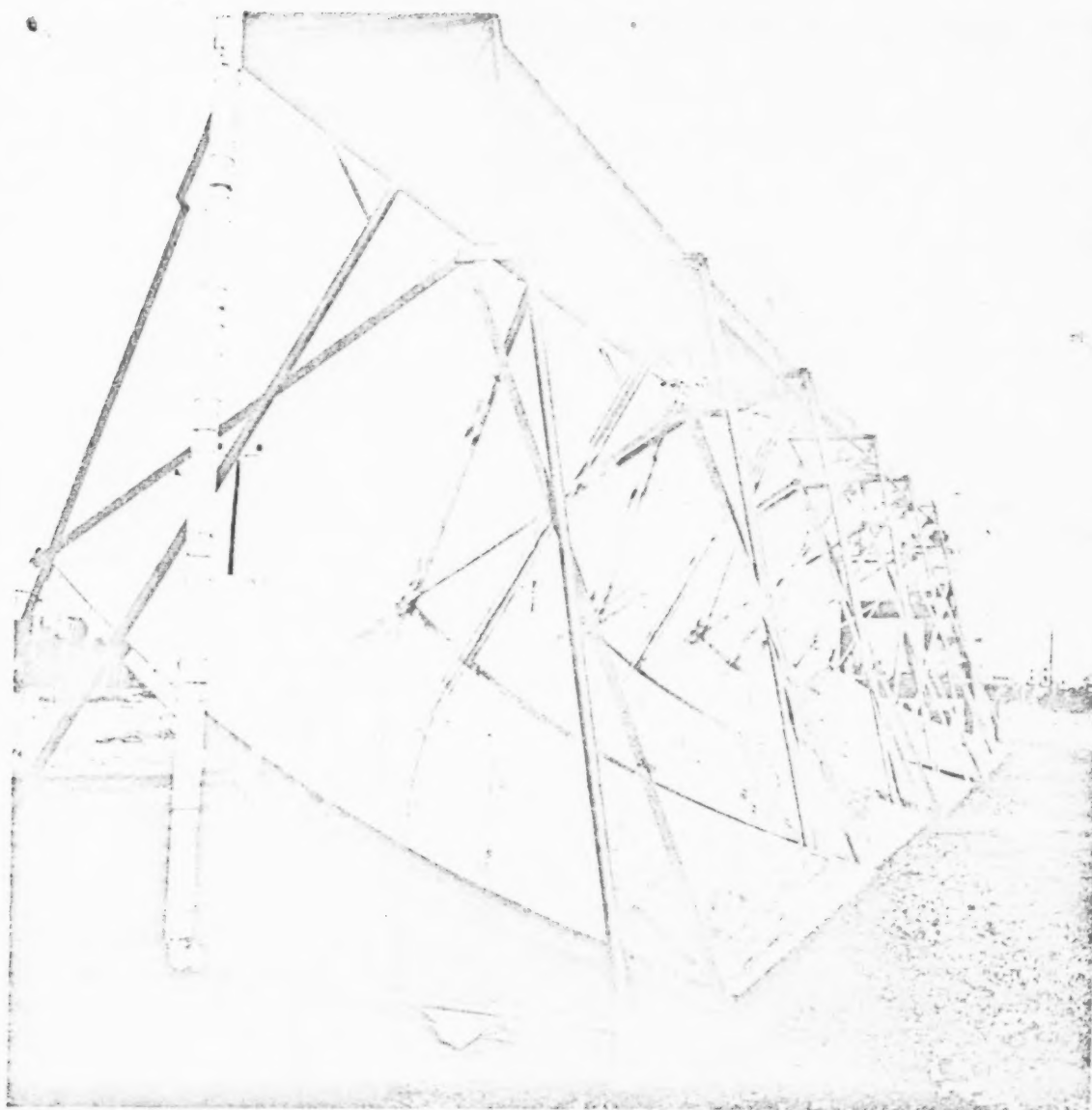
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# **SOLAR ENERGY**

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**Change of Title:** The Association for Applied Solar Energy wishes to announce that, beginning with this issue, the *Journal of Solar Energy Science and Engineering* will henceforth be entitled *Solar Energy: the Journal of Solar Energy Science and Engineering*.

**Submission of Papers:** The Association's policy in the publication of the *Journal* is to provide a medium where original papers on all aspects of solar energy measurement, collection, and utilization may appear in such a form that they will become part of the permanent literature of the subject. To that end, submission of such papers by research workers throughout the world is invited.

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# PLASTIC GLAZINGS FOR SOLAR ENERGY ABSORPTION COLLECTORS\*

By FRANK E. EDLIN

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This paper presents information comparing three transparent plastic films with glass as glazings for solar energy absorption collectors. Data concerning the transmittance characteristics of these films are included, together with information concerning other physical properties such as tensile strength, index of refraction, and weathering characteristics.

## INTRODUCTION

Economical collection of solar radiation at moderate temperatures is one of the most challenging problems facing investigators in the field of solar energy utilization. Virtually all absorption collectors proposed to date to accomplish this function depend upon the use of a glazing which is essentially transparent to the solar spectrum and substantially opaque to long, or infrared, wavelength radiation. Such a glazing plays a vital role in allowing the incident solar radiation to enter the device and substantially restricting infrared energy losses through reradiation.

## DISCUSSION OF GLAZES FOR SOLAR ABSORBERS

The energy which is obtainable from a solar absorptive collector is the product of: (1) the fraction of the incident solar radiation which is transmitted through the glazing; (2) the fraction of the transmitted radiation which is absorbed by the interior surfaces and is not lost from the device through conduction, reradiation, and convection. It is therefore important that the glazing have a high transmittance value for the solar spectrum and that it be opaque to long wavelength radiation from the interior surfaces of the collector. Quite as important to the engineer as the optical properties are the physical properties of the glazing. He is principally concerned in the case of plastic films with the tensile strength, thermal coefficient of expansion, specific gravity, elastic modulus, melting or softening point, and thermal conductivity. He must also be concerned with exposure life and with costs.

Many excellent studies<sup>5, 6, 7, 8, 9</sup> have been reported of the optical and mechanical properties of glass as a glazing, and many of these have included values of the transmittance as a function of the angle of incidence. The fragility and weight of glass, however, constitute major handicaps

which are not encountered with glazings constructed from clear plastic films.

New weather-resistant plastic films are now being developed which offer promise as glazings for solar energy absorptive collectors. Properties of three of these are presented in Table I. Like glass, plastic films have structural disadvantages which must be considered when using them as glazings for solar energy collectors. Of first importance, perhaps, is the factor of weatherability.

TABLE I  
PHYSICAL PROPERTIES OF TEFLON 100-X,\*  
WEATHERABLE MYLAR,\*\* AND POLYETHYLENE FILMS

	Teflon 100-X	Weatherable Mylar	Polyethylene
Thermal conductivity (Btu/hr/sq ft/in./°F)	1.35	1.05	1.6
Melting point, °F	550	482	224
Specific gravity	2.15	1.39	0.914
Refractive index	1.34	1.65	—
Thermal coefficient of linear expansion, °F	$29 \times 10^{-5}$	$20 \times 10^{-6}$	$5.1 \times 10^{-5}$
Tensile modulus of elasticity, psi	50,000	550,000	30,000
Tensile strength, psi, 73°F	2,900	24,000	2,500
212°F	1,400	18,000	700
Sq yd/lb/0.001 in. thickness	10	15.4	22.8

\*"Teflon 100-X film" is the experimental code designation of a new Teflon FEP fluorocarbon film now being evaluated. Commercial quantities are not yet available.

\*\*Weatherable Mylar is a new weather-resistant polyester film which has been made available recently on the commercial market.

Weather-resistant clear plastic films which are suitable for glazings are of two general types. The first type is so constituted chemically as to be transparent to essentially all of the solar spectrum, including those wavelengths which accelerate degradation of the plastic. An extrudable Teflon composition, designated Teflon FEP fluorocarbon film, is a material of this type. Another film of the Teflon family, also of this type, made, however, by casting techniques, is available on a limited commercial scale in thicknesses of from 1 to 4 mils. This cast film has outdoor exposure life, physical properties, and solar characteristics approximately equivalent to those of extruded Teflon FEP

\*Paper presented at the annual meeting of the American Society of Mechanical Engineers, New York City, December 1-6, 1957.

fluorocarbon film. It may be obtained with a hydrophilic, or wettable, surface.

The second type, exemplified by Mylar polyester film, has the property of reflecting those wavelengths which would otherwise promote degradation and of transmitting a major fraction of all other wavelengths. Clear polyethylene film has absorption characteristics intermediate between these two types, absorbing within its molecular structure some of the incident energy which tends to promote failure under outdoor conditions. Outdoor exposure life of a film is also affected by the chemical resistance offered to hydrolysis, oxidation, and other chemical attack and by mechanical damage from flexing, wind ripple, and other stresses. At normal ambient temperatures, the outdoor exposure life of a well-supported Teflon-type film is limited only by mechanical failure and when thoroughly supported is unaffected by atmospheric conditions for periods well in excess of 15 years,\* although a shorter life may be expected for usual solar applications. Weatherable Mylar polyester film would appear to have a somewhat shorter life but is still quite satisfactory for many glazing applications, and is many times more resistant to outdoor conditions than is clear polyethylene film.

The spectral transmittance of Teflon FEP fluorocarbon film, weatherable Mylar, and clear, single-strength window glass is shown in Fig. 1, and compared to the spectral distribution of solar radiation. When two or more superimposed glazings are to be used, and the outermost plastic film is of the first type, transparent to the entire solar spectrum, the succeeding inner films should also be of radiation-resistant material. However, use of a selectively transparent film of the second type as the outer glazing may permit use of inner films which are considerably less radiation-resistant.

## EXPERIMENTAL TECHNIQUE

A valid comparison of the optical properties of these films with those of glass requires that we have information concerning their performance in transmitting inci-

\*Exposure life of both Teflon FEP fluorocarbon and weatherable Mylar films are estimated from accelerated exposure tests and from outdoor exposure tests in Florida which are not yet completed.

FIG. 1 — Spectral transmittance of glass, weatherable Mylar, and Teflon 100-X, compared with the solar spectrum.

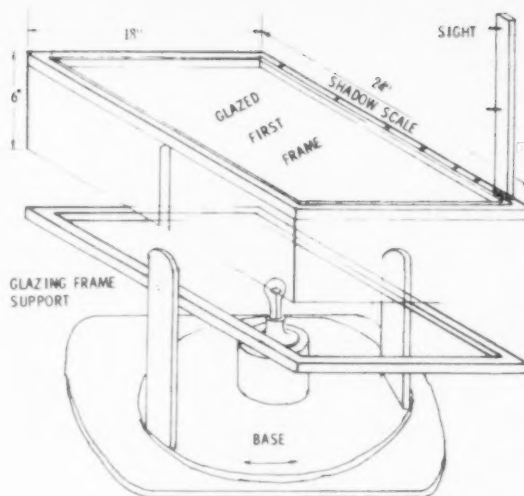
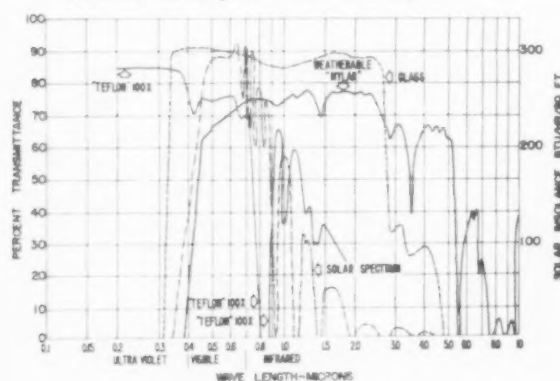


FIG. 2 — Test equipment.

dent solar radiation as a function of the angle of incidence. The test equipment sketched in Fig. 2 was used to secure this information. It consisted of a glazing frame supported with an altazimuth mounting such that a standardized Eppley pyrheliometer was located on the axis of inclination. The test pane was located 3 in. above the pyrheliometer element. Several test frames of each glazing material were provided including one frame which was surrounded by a 6-in. skirt of the same material. A vertical post and sight on the frame had a shadow scale calibration on its side which quickly provided the solar angle of incidence. The solar altitude was also easily obtained as the complement to the angle of incidence when the test frame was horizontal. This equipment permitted a series of readings to be taken as rapidly as the pyrheliometer would come to equilibrium. The transmittance was obtained by dividing the energy received at the pyrheliometer with the glazing in position by that received when the glazing was removed.

Data obtained are presented in Table II. These have been plotted for ready reference in Fig. 3, which relates the transmittance for Teflon FEP fluorocarbon film, weatherable Mylar polyester film, polyethylene, and glass as a function of the angle of solar incidence. Fig. 4 shows the variation in transmittance obtained with varying solar altitudes using the same glazing materials. This variation results from the altered composition of the solar spectrum as the solar altitude changes and from the response of these glazing materials to this altered spectral distribution. It is seen from Fig. 3 that of the three films Teflon FEP fluorocarbon film is superior in solar transmittance to glass, while the others are somewhat inferior.

The films used were of 2-mil thickness, while the glass was clear, single-strength standard window pane having a normal transmittance at normal incidence of 0.93. Correlations of the transmittance and reflectance as a function of pane thickness have been reported for glass.<sup>5,9</sup> For clear films, however, we were unable to establish a dependable correlation between transmittance and film thickness

TABLE II  
TRANSMITTANCE OF SOLAR ENERGY THROUGH  
GLASS AND PLASTIC FILM

A. Transmittance as a Function of the Angle of Incidence

	Date	Per cent transmittance					
		0°	15°	30°	45°	60°	75°
Teflon 100-X	5/ 8/57	97.2	97.0	96.0	92.5	87.5	64.0
	7/ 7/57	97.1	96.8	95.5	94.0	82.3	65.0
	7/19/57	97.5	97.0	95.0	93.0	88.3	63.0
	9/ 1/57	97.0					
	Avg.	97.1	96.8	95.5	93.1	86.0	64.0
Weatherable Mylar	5/ 8/57	85.0	84.5	83.0	81.0	77.0	66.0
	7/ 7/57	84.8	83.7	82.3	81.6	77.0	60.0
	7/19/57	85.0	84.2	83.2	80.8	77.5	62.5
	9/ 1/57	85.8					
	Avg.	85.1	84.1	82.8	81.1	77.1	62.8
Clear Polyethylene	5/ 8/57	92.1	91.0	90.0	87.0	82.0	64.0
	7/ 7/57	91.8	90.9	90.0	88.7	84.0	63.0
	7/19/57	91.8	91.5	90.5	89.0	86.0	64.0
	9/ 1/57	92.0					
	Avg.	91.9	91.1	90.1	88.2	84.0	63.7
Window Glass	5/ 8/57	92.8	92.7	92.6	90.5	84.0	62.0
	7/ 7/57	93.0	92.7	92.0	90.6	82.5	62.0
	7/19/57	92.5	92.0	91.8	91.0	83.0	55.0
	9/ 1/57	92.7					
	Avg.	92.7	92.4	92.1	90.7	83.1	59.7

B. Transmittance as a Function of Solar Altitude  
(Wilmington, Del.)

	Date	Per cent transmittance			
		58°	36°	16°	10°
Teflon 100-X	9/1/57	97.0	95.1	96.0	97.0
Weatherable Mylar	9/1/57	85.8	85.0	82.7	80.7
Clear Polyethylene	9/1/57	92.0	91.3	88.2	87.3
Window Glass	9/1/57	92.7	92.8	92.3	92.0

Standard Eppley Pyrheliometer #3135, 2.38 mv/gm-cal/sq cm/min

for films varying between 1 and 5 mils. The variation in transmittance was too small for observations to be made of sufficient accuracy to establish a valid relationship.

Atmospheric cloudiness decreases the total incident solar radiation and increases the ratio of diffuse to direct radiation. The limited amount of work done was insufficient to enable us to obtain dependable correlations of transmittance with total incident radiation or with the ratio of diffuse to direct radiation. Isolated readings showed,

FIG. 3—Transmittance of glass and weather-resistant plastic glazing with respect to the angle of incidence.

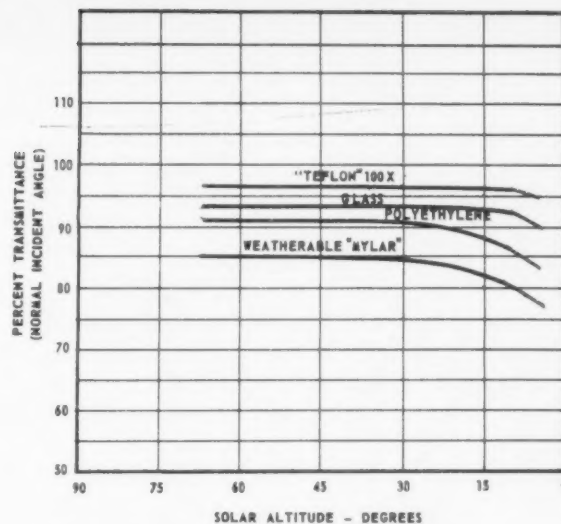
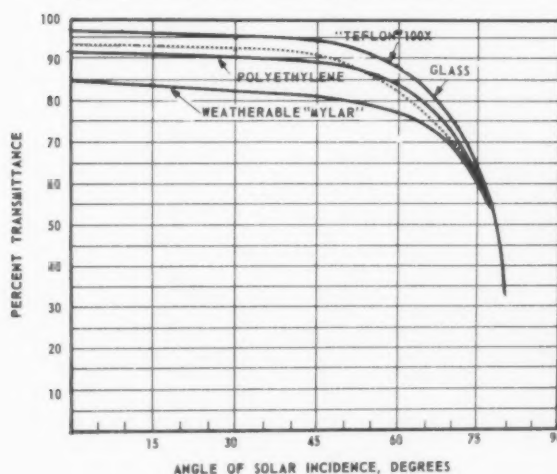


FIG. 4—Transmittance as a function of solar altitude.

however, that the best of the glazings tested, Teflon FEP fluorocarbon film, transmitted only 88 per cent of the gross incident energy on overcast days of uniform cloud cover in which the position of the sun could just be detected, while on clear days this figure was increased to the range of 96.5 per cent. When atmospheric conditions were such as to cause a uniform decrease of as much as 15 per cent in total insolation, there was no measurable change in transmittance.

After a year of outdoor exposure in absorptive collectors, both Teflon FEP fluorocarbon and Mylar polyester films showed the same transmittance as did new film. It is expected that after a sufficiently long period of exposure, however, some degradation would be obtained in plastic films.

## CONCLUSION

The data plotted in Figs. 3 and 4 permit a comparison between the three films studied and glass as solar absorption collector glazings for any angle of incidence and for any solar altitude. Although a measure of uncertainty remains concerning response to long-term exposure and to heavy cloud cover, it is believed that the data obtained will permit the designer of solar energy absorption collectors to give consideration to plastic films as glazings.

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# ENGINEERING RESEARCH WITH A SOLAR FURNACE\*

By PETER E. GLASER

Arthur D. Little, Inc., Cambridge, Massachusetts

Research approaches using a solar furnace for the measurement of properties of matter and testing of materials at high temperatures under controlled conditions in the laboratory are discussed. Instruments to measure temperatures, heat flux, and flux density are described, and their uses pointed out. Methods for measuring thermal conductivity, thermal expansion, heat content, and emissivity of materials are explained, and the analytical and experimental procedure outlined.

## INTRODUCTION

The necessity for technological control of matter at high temperatures has become more and more pressing with the development of such equipment as gas turbines, missile nose cones, rocket motors, and nuclear reactors. Today, engineers still have to make educated guesses regarding the behavior of materials under conditions of extreme temperatures and unfavorable environments. They are faced with the problem of selecting the most suitable materials and then testing them under these conditions. Before this testing can take place, high temperatures must be generated under controlled conditions in the laboratory. One promising method is the use of an optical system to concentrate radiation from the sun in a solar furnace.<sup>1</sup> In the last few years, such furnaces have received considerable attention, and their basic principles, characteristics, and design features have been established.<sup>2</sup> Solar furnaces have proved to be promising research tools for the measurement of high-temperature properties of materials and for materials testing.<sup>3</sup> Their popularity is evidenced by the fact that nearly forty of them are in existence in this country.

A solar furnace eliminates contamination of the sample by unfavorable environmental factors, since the heat source is far enough from the sample to transmit heat by radiation only, rather than by conduction or convection. In addition, materials can be tested either in air or in a controlled atmosphere, and measuring instruments can be brought close to the samples without being subjected to excessive heat.

## PHYSICAL MEASUREMENTS

Although temperatures up to 3500° could be conveniently generated in a solar furnace, methods of measuring physical properties at high temperatures had to be developed.

### (1) Temperature

Conventional optical pyrometers accurately measure only the temperatures of blackbodies—a condition that few samples are able to satisfy. Although drilling small holes into the sample surface to approximate blackbody conditions is theoretically valid, this expedient raises questions concerning the uniformity of cavity temperatures.

Accurate temperature measurement hinges on reasonably accurate knowledge of the spectral emissivity at  $0.65\mu$ .

The spectral emissivity at this wavelength is determined from measurement of the reflected solar flux and use of the relation  $\epsilon_\lambda = 1 - r_\lambda$ , where  $r_\lambda$  is the spectral reflectivity.

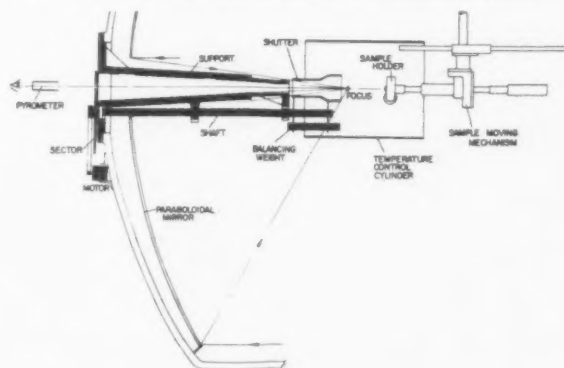
As shown in Fig. 1, a shutter is used in conjunction with this instrument to separate the emitted and incident radiation.

### (2) Heat Flux

Fig. 2 shows a high-radiation calorimeter designed to measure the heat flux reaching the focal zone of the collecting mirror.<sup>4</sup> This calorimeter can be exposed to flux

\*Paper presented at the annual meeting of the American Society of Mechanical Engineers, New York City, December 1-6, 1957.

Fig. 1 — Shutter to separate emitted and incident radiation.



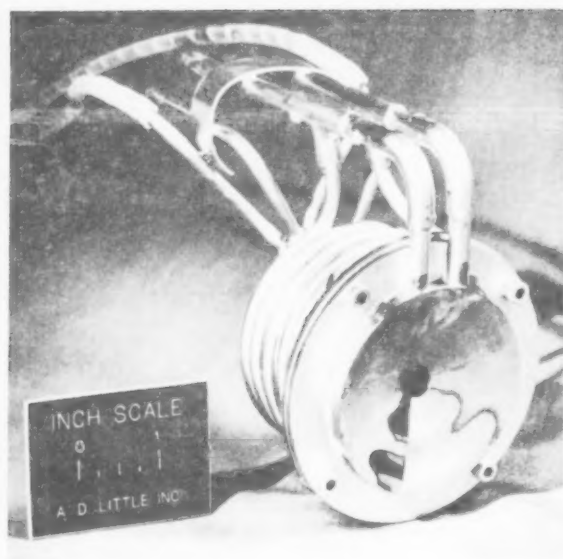


FIG. 2 — High-radiation flux, absolute, water-cooled calorimeter.

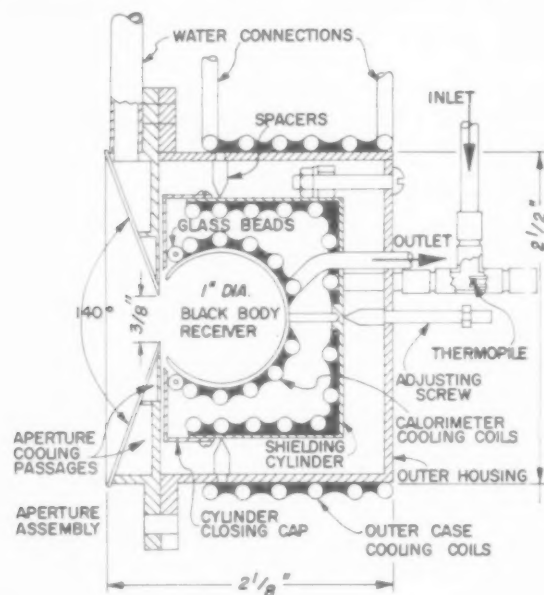


FIG. 3 — Design details of calorimeter.

densities of the order of  $4 \times 10^8$  Btu per sq ft per hr for extended periods without deterioration. Fig. 3 shows the design details of the calorimeter, which consists of a black-body receiver provided with a cooled aperture and a cylindrical housing. The optical properties of the paraboloidal mirror cause a gaussian distribution in the heat flux reaching the sample. This distribution can be measured with a water-cooled radiometer designed to withstand the high heat flux.<sup>5</sup> The 0.1-cm diameter of the energy-receiving disc permits fine measurement of the flux distribution.<sup>6</sup>

With these instruments, it is possible to calibrate a

solar furnace under various conditions that relate incoming radiation energy (e.g., measured with a pyrheliometer) to the radiation flux at the focal zone. Thus, the necessary information on the sample exposure can be obtained without the installation of a calorimeter for an individual measurement.

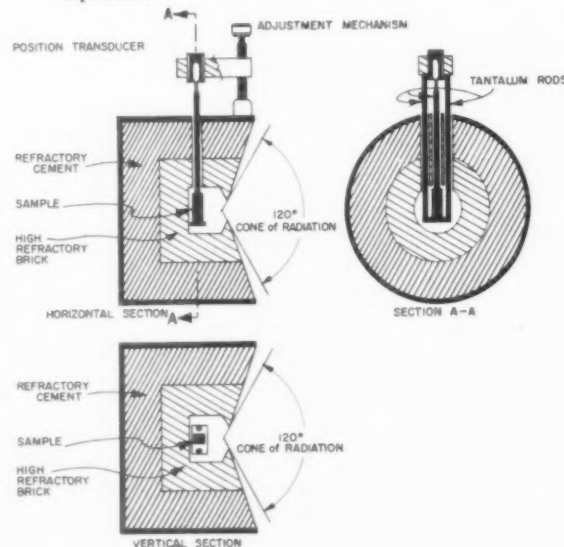
### (3) Thermal Properties

#### (a) Thermal Conductivity

The difficulties of obtaining reliable data on thermal conductivity in the moderate temperature ranges are generally recognized. Obtaining such data in the high-temperature ranges is far more difficult, and hardly any information exists for above  $1500^\circ\text{C}$ . It is hoped that the following method, applicable to conditions in a solar furnace, can alleviate this condition.

The thermal conductivity and diffusivity of a poor conducting material can be obtained from the analytical solution of a heat-conduction problem. (See Appendix I for derivation.) From this solution, and on the assumption that thermal properties are independent of temperature, the temperature rise in a semi-infinite solid under the influence of a circular disc source with a uniform and constant heat flux can be calculated. If the temperature rise in a short time interval at a point along the disc axis is measured, thermal diffusivity can be calculated. Then, by substitution of this value in the original equation at the previously measured temperature, time, and position, thermal conductivity can be calculated. The value of thermal conductivity thus obtained corresponds to the temperature difference between the surface and the point inside the body. If a point near the surface is chosen, the temperature difference can be kept small, and approximate average values for thermal diffusivity and thermal conductivity can be obtained even when these properties show a weak dependence on temperature.

FIG. 4 — Dilatometer for measurement of differential thermal expansion.



### (b) Thermal Expansion

The measurement of thermal expansion at high temperatures is of considerable interest, particularly where refractory materials that may be subject to thermal shock are used. Such measurements can provide data on dissociations, allotropic transformations, and the formation of solid solutions.

Fig. 4 shows a cavity-type dilatometer for measuring thermal expansion of materials. Heating the sample in a cavity<sup>8</sup> ensures that most of the incident energy is captured. The temperature rises progressively as energy accumulates in the cavity; the maximum value is limited by conductive losses across the walls and the radiation through the cavity opening. The cavity temperature, and consequently, the rate of heating or cooling during a test run, can be very closely regulated by the admission of a greater or smaller amount of energy.

The amount of radiation captured in the cavity permits the treatment of samples up to 2 in. long. The sample, in the form of a rod, is suspended by two tantalum rods in a cavity formed of high refractory materials. An additional tantalum rod is connected to a sensitive transducer to measure the thermal expansion of the sample. The sample can be tested in a neutral atmosphere or in a vacuum if a suitable window is used to close the cavity.

### (c) Heat Content

Because of the physical difficulties of generating high temperatures in a controlled environment,<sup>9</sup> little high-temperature heat-content data is available on the more common materials. Heating a sample in a cavity-type

FIG. 5 — High-temperature, aneroid calorimeter for heat-content measurements.

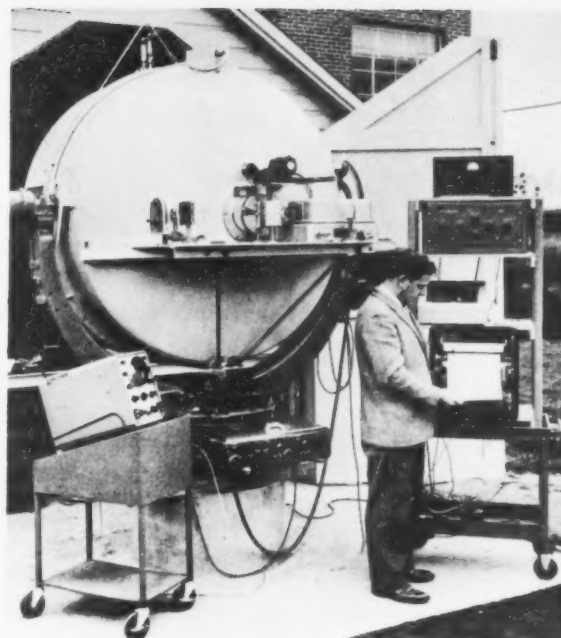
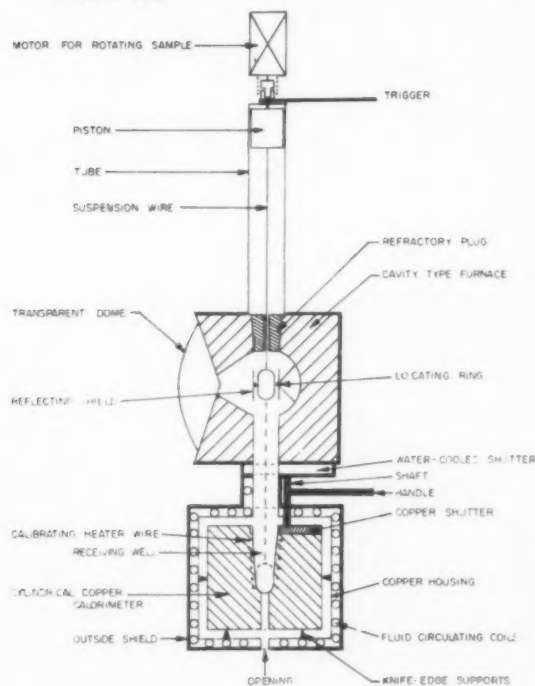


FIG. 6 — Apparatus for emissivity measurements.

furnace by radiant energy, however, permits temperatures of about 2500°C to be obtained. Fig. 5 shows an apparatus designed for heat-content measurements in a solar furnace. It consists of two parts: a cavity-type furnace, in which the material is heated; and an aneroid drop calorimeter, where heat of fusion, heat of transition, and total heat content of substances can be measured.

The sample is contained in a suitable capsule held inside the cavity by locating rings and surrounded by a highly polished reflecting cylinder where the inside surface has been blackened. This blackening prevents uneven heating of the sample. The capsule is suspended by a pair of thin wires that also act as the thermocouple by measuring the temperature of the sample. (For measurement of higher temperatures, an optical pyrometer can be used.)

The suspension wires pass through a small hole in a refractory plug and are attached to a small piston. The piston, after release, is cushioned by the compression of the gas inside the tube; the sample is dropped into the calorimeter below the cavity.

### (4) Emissivity

The spectral emissivity of solid materials from the near-infrared to 15 $\mu$  can be conveniently measured in the solar furnace. In a typical study, the temperature range of interest extends from 1000 to 3500°K. The materials being studied include metals, refractories, and refractory-coated metals. The advantage of using the solar furnace is that the sample alone is heated and stray radiation completely excluded. With other methods of heating, it is difficult to exclude stray radiation emitted by the furnace and objects other than the sample. Fig. 6 shows the apparatus in position on the solar furnace; a Perkin Elmer

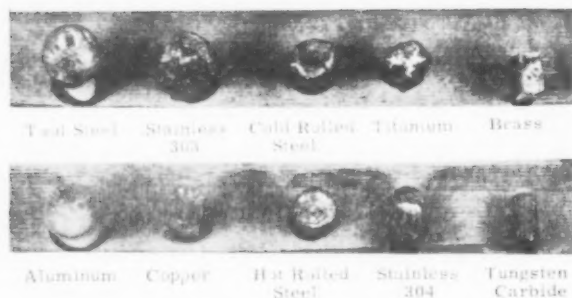


FIG. 7 — Metal samples after heating in air in the solar furnace.

Universal Monochromator is used in conjunction with an optical system.

### MATERIALS TESTING

Solar furnaces have been used in a wide variety of tests to simulate conditions in extreme-temperature applications. The advantages of this method are that the samples are heated in air, and close observation of the behavior of materials possible. Fig. 7 shows several metals after they were exposed in air to the temperatures attainable in a solar furnace.

### CONCLUSION

At present only isolated literature references<sup>10</sup> have reported on experimental procedures for use in a solar furnace. As wider use of this research tool is made, the advantages of the solar furnace will be more fully realized, since the research possibilities are limited only by the ingenuity of the experimenter. Testing procedures now being developed will demonstrate that engineers not only have solved the problem of generating high temperatures, but also are able to solve research problems in the new field of pyrogenics.

### APPENDIX I

The temperature rise as measured along the axis of a circular disk source can be expressed as

$$\theta(z, t) = \frac{Q}{k} \left[ 2 \left( \frac{at}{\pi} \right)^{1/2} \left( \frac{z^2}{e^{4at}} - \frac{a^2 + z^2}{e^{4at}} \right) \right. \\ \left. - z \operatorname{erfc} \frac{z}{(4at)^{1/2}} + (a^2 + z^2)^{1/2} \operatorname{erfc} \left( \frac{a^2 + z^2}{4at} \right)^{1/2} \right] \quad [1]$$

where

$d$  = diameter of source       $t$  = time  
 $\theta$  = temperature       $Q$  = flux density  
 $z$  = position along axis       $k$  = thermal conductivity of disk source

The experimental procedure will be used to provide the temperature distribution along the axis at any time.

Let  $\theta_1$  and  $\theta_2$  be the two temperatures at corresponding distances  $z_1$  and  $z_2$  along the axis at a time  $t_a$ . Then put

$$\eta = \frac{\theta_1}{\theta_2} = \frac{\frac{Q}{k} f(a, t_a, z_1)}{\frac{Q}{k} f(a, t_a, z_2)}$$

Provided that the temperatures are not too different,  $k$  will not vary significantly between  $\theta_1$  and  $\theta_2$ .

Hence

$$\eta = \frac{f(a, t_a, z_1)}{f(a, t_a, z_2)}$$

From this, solve for  $a$  by successive approximations.

On substituting  $a$  in Equation [1], thermal conductivity can be calculated at  $t_a$  and  $z_1$  or  $z_2$ .

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# PHOTOCHEMICAL ASPECTS OF SOLAR ENERGY UTILIZATION

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The present outlook for a practical procedure for chemically converting solar energy is something short of optimistic. None of the known endothermic reactions, per se, approach the minimal criteria of a high quantum yield, a broad action spectra extending through the visible and a large positive  $\Delta F^\circ$ . The majority of the known reactions proceed at wavelengths below about 4000 Å — a region which accounts for only 4 per cent of the incident solar energy. Clearly, the greatest need at this time is for photosensitizers which will extend the action spectra well into the visible portion of the solar spectra. Some small beginnings in this respect have been made with the cerous-ceric sensitized decomposition of water in the ultraviolet. The zinc oxide sensitized formation of hydrogen peroxide also proceeds in the ultraviolet. However, in this instance, other solid-state catalysts have been described which bring about hydrogen peroxide formation well into the visible. Unfortunately, the yields of  $H_2O_2$  are very small. The possibility of utilizing organic dyestuffs together with solid state catalysts may hold some promise, though this approach has not been pursued. The photodecomposition of nitrosyl chloride, on the other hand, proceeds well into the visible. The gaseous products can be removed from the system, thereby avoiding the photostationary state. Perhaps the major intrinsic shortcoming of this system is the small standard free energy change.

## INTRODUCTORY AND HISTORICAL

It is one of the ironies of our scientific progress that, despite the enormous strides, one of the most commonplace and important processes, photosynthesis, is so incompletely understood and far removed from technological mastery. The conversion of radiant solar energy to a usable chemical form is a process which has occurred in nature since the beginnings of life. However, all attempts to set up even a relatively simple chemical system capable of efficiently converting solar energy have been met with disappointment. The situation in this field is such that a considerable amount of work remains to be accomplished on the research level, and the emphasis of this review is

placed accordingly. A detailed discussion of photosynthesis occurring in green plants has been omitted from this review. Attention is focused on several of the more promising and much simpler reactions. However, because of the importance of photosynthesis, it is frequently used as a basis of comparison in the evaluation of other reactions; and a few remarks concerning it may be in order here.

Photosynthesis was, in fact, the first photochemical reaction studied. The earliest work, usually attributed to Stephan Hales, was *Vegetable Staticks*, published in 1727. The work was continued in the latter half of the 18th century, notably by Priestley, Ingen-Housz, Senebier, and de Saussure.<sup>1</sup> These early workers were fully aware of the important role played by light. However, the modern statement is due to J. R. von Mayer, who in 1845 realized that the function of sunlight is to provide the energy required for photosynthesis and that the energy that is recoverable from the photosynthetic products is ultimately attributable to that absorbed from sunlight. This statement of the situation, however trivial it may appear today, required the demolition of the caloric theory of heat and the establishment of present-day concepts of energy and its conservation. About the same time, that is toward the middle of the last century, Draper, Bunsen, and Roscoe were pioneering in the field of quantitative photochemistry.

This period, then, marks the beginning of our present subject. However, it is interesting to note that a lapse of nearly seventy years occurred prior to the publication of Warburg and Negelein<sup>2</sup> on the quantum efficiency of photosynthesis. These workers reported a quantum efficiency of 0.25 (molecules  $CO_2$ /photons absorbed) corresponding to about 70 per cent energy storage (energy recoverable from products/energy absorbed). Later studies by Daniels<sup>3</sup> and others<sup>4</sup> gave a much lower quantum efficiency of about 0.10-0.12 corresponding to about 30 per cent energy storage. The percentage of the *total* solar energy that is utilized is considerably less since radiation in the infrared (accounting for about 50 per cent of the total) is not effective, and within the visible only certain wavelengths are appreciably absorbed. Consequently, even under optimal laboratory conditions, the over-all efficiency (recoverable energy/total incident energy) is probably less than 10 per cent. In nature, the over-all efficiency is

TABLE I  
EFFICIENCY OF THE TRANSFORMATION OF SOLAR RADIATION BY MEANS OF VARIOUS DEVICES OR  
PROCESSES INTO HEAT OR ELECTRICITY

Method of conversion or device for transformation	Efficiency of device or process %	Efficiency of transformation into heat %	Efficiency of transformation into electricity %
(a) Transformation of radiation into heat in a solar boiler with a paraboloidal reflector	65-75	(a) 65-75	(a + b + c) 5-15
(b) Transformation of the heat of steam into mechanical energy in steam engine or turbine	10-20		
(c) Transformation of mechanical energy into electricity	90-95		
(a) Steam of low pressure (2-5 atm) in a solar boiler with a paraboloidal reflector	45-55	(a) 45-55	(a + b + c) 2-6
(b) Transformation of the energy of the steam into mechanical energy	5-10		
(c) Transformation of mechanical energy into electricity	90-95		
Solar heaters, solar cookers with reflectors	50-60	50-60	
Solar heaters of the hot-box type for heating water up to 55-60° (transformation of this heat into mechanical energy not worthwhile)	30-45	30-45	
(a) Transformation of solar radiation into heat for thermo-electrogenerators in installations with paraboloidal reflectors	60-70		(a + b) 2.5-3.5
(b) Transformation of heat in thermo-electrogenerators into electricity	4-6		
Transformation of solar radiation into electricity in photocells (Bell Telephone Laboratory figures)	up to 5 and even 11		5-11
(a) Growing of forests in natural conditions for firewood	0.5-1.5	(a + b)	(a + b + c)
(b) Burning of wood in furnace of boiler	70-80	0.35-1.2	0.03-0.34
(c) Mechanical energy obtained from steam	10-30		
(d) Transformation into electricity	90-95		
Natural processes of the transformation of radical energy obtained at hydro-power stations	0.002		0.002
(a) Transformation of solar radiation by plants into potential chemical energy — natural photosynthesis	0.25-1		(a + b) 0.0075-0.05
(b) Transformation of the chemical energy of green fodder into muscular energy by animals (oxen, horses)	3-5		

still smaller, since the average growing season occupies about one-third of the year; the concentration of  $\text{CO}_2$  is low; and the light intensity is high. Because of these and other reasons, the over-all efficiency in nature is estimated at about 0.1-0.2 per cent.<sup>3</sup>

The complexity of photosynthesis has understandably turned attention to the much simpler reactions discussed in a later section. The over-all efficiency of these reactions is low, being in the order of a few per cent or less. By way of comparison, the efficiency of various mechanical systems is given in Table I.<sup>5</sup> It can be seen that the efficiency associated with the transformation of solar energy into thermal energy is about 60-65 per cent, and it may be added that in some cases higher figures have been obtained. Of course, further conversion to electrical energy results in much lower over-all efficiencies.

One of the major difficulties associated with the development of an effective mechanical system is the energy storage problem. Unless the energy is to be utilized immediately, it must be stored by heating gravel, water, or some other media. Such storage devices are large and cumbersome and require careful insulation. Even under the best of conditions, the thermal energy is eventually dissipated. Chemical systems, on the other hand, possess the inherent advantage that the reaction products can be stored for an

indefinite period of time. Recovery of the absorbed energy can be achieved by reversing the initially endothermic reaction. The temperature achieved depends primarily on the rate and enthalpy (heat) of the reverse reaction. The efficiency of the collecting and storage systems for chemical convertors is, therefore, essentially independent of the operating temperature at the output end. Such is not the case with conventional flat-plate collectors. Increasing the operating temperature requires an increase in the collector-plate, working-media, and storage temperatures with an inevitable decrease in collector-plate and storage efficiency. The heat losses due to radiation alone, for example, increases as the fourth power of the collector-plate temperature.

### PHOTOCHEMICAL PRINCIPLES

In this section some of the more frequently required background information and data are summarized for purposes of reference.

#### Nomenclature

- $\text{\AA}$  . . . Angstrom unit ( $10^{-8}$  cm)
- $c$  . . . concentration (moles/liter)
- $d$  . . . mean free path
- $\Delta E^*$  . . . activation energy
- $\Delta F^\circ$  . . . change in free energy when both the initial and final states of the system are at 298°K and at

	standard conditions (usually taken as unit fugacity or activity)
$\Delta F^*$	free energy of activation
$\Delta H^*$	enthalpy of activation for forward reaction (kcal/mole)
$\Delta H$	change in enthalpy of a system (kcal/mole)
$h$	Planck's constant ( $6.624 \times 10^{-27}$ erg/sec)
$I_{\nu}$	intensity of incident radiation at wavelength $\lambda$ (einsteins sq cm)
$I_{\lambda}$	intensity of radiation at wavelength $\lambda$ at some position $d$ within the system
$k$	Boltzmann constant value
$k$	rate constant for forward reaction
$k_{-1}$	rate constant for reverse reaction
$K_{\lambda}$	absorption coefficient at wavelength $\lambda$
$l$	length of absorption path (cm)
$N$	Avogadro's number ( $6.02 \times 10^{23}$ )
$p$	pressure
$R$	gas constant ( $8.3144 \times 10^7$ ergs deg $^{-1}$ )
$\sigma$	molecular diameter
$\Delta S$	change in entropy of a system (cal/deg)
$\Delta S^*$	entropy of activation (cal/deg)
$T$	temperature ( $^{\circ}$ K)
$\phi$	quantum yield of a reaction: no. of moles of product formed per einstein of light absorbed. It is (in general) a function of the frequency of the incident radiation.
$\bar{\phi}$	average quantum yield
$\phi_{\lambda}$	quantum yield at wavelength $\lambda$
$\lambda$	wavelength of light
$\nu$	frequency of light

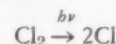
The *initial* photochemical act involves the absorption of one photon by each molecule which is activated. The energy associated with a photon is given by the well-known expression,  $E = h\nu$ . However, it is frequently convenient to refer to the energy associated with an Avogadro number ( $6.02 \times 10^{23}$ ) of photons which is defined as one einstein of radiation. The energy associated with an einstein of radiation is  $Nh\nu$ , i.e.,

$$Nh\nu = \frac{2.86 \times 10^5}{\lambda(\text{\AA})} \text{ kcal} = \frac{11.35}{\lambda(\text{\AA})} \text{ Btu} \quad [1]$$

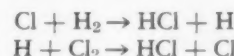
Following absorption, the molecule will undergo transition in vibrational, rotational, and electronic energy states depending on the energy of the absorbed photon. From the viewpoint of photochemistry, transitions involving the electronic states are of greatest interest since these are sufficiently energetic to result in the chemical alteration of the molecule. Such transitions occur in the visible and ultraviolet range of the spectrum and correspond to about 40 kcal per einstein (7000\AA) to 100 kcal per einstein (2800\AA). The photochemical activation may be followed by a great number of primary processes: (a) fluorescence-emission of the absorbed radiation; (b) deactivation by collision with other molecules or with the sides of the containing vessel; (c) direct dissociation into simpler molecules, atoms, or free radicals; (d) dissociation caused by collision with other molecules; (e) internal rearrangement (isomerization) into the final product; (f) one or more different reactions with normal molecules; (g) transfer of energy to normal molecules by means of inductive resonance transfer.

These possible dispositions of the energy associated with the electronically excited molecule are referred to as the photochemical primary processes and are limited in each case to a maximum quantum yield,  $\phi$ , of one (i.e.,  $\phi$  = molecules of product per total number photons ab-

sorbed). However, following the photochemical primary processes, secondary reactions may occur which will determine the over-all yield of the processes. Chain reactions may occur, because of the formation of atoms or free radicals leading to high quantum yields of the final product. Thus, the photoactivation of a mixture of  $H_2$  and  $Cl_2$  results in the primary event



Each chlorine can interact with  $H_2$  to instigate a chain reaction,



The final quantum yield of HCl can in such cases be very high. Conversely, deactivation, fluorescence, recombination of the primary products in the reverse reaction, or side reactions forming products other than the principle products will result in a low quantum yield. A more complete discussion of this matter may be found in standard works such as that of Noyes and Leighton.<sup>6</sup>

The mere absorption of a photon by a molecule does not necessarily result in a chemical reaction. In order for the primary reaction to occur, the energy of the excited molecule must be equal to or greater than a certain quantity which is referred to as the *activation energy*,  $\Delta E^*$ . The reaction energetics of a simple diatomic molecule  $AB$  is shown in Fig. 1. The potential energy of the molecule is plotted as a function of the distance between  $A$  and  $B$ . When the molecule absorbs light, it will undergo a transition to an excited electronic and vibrational state; and the distance between atoms will, on the average, increase. If the excited molecule has an energy equal or greater than the activation energy,  $\Delta E^*$ , it can undergo decomposition, in this case, to give the products  $A$  and  $B$ . The rate of reaction,  $k$ , can be shown by quantum statistical considerations to be<sup>7</sup>

$$k = \frac{RT}{Nh} e^{-\Delta F^*/RT} \quad [2]$$

where  $\Delta F^*$  is the standard free energy of activation.

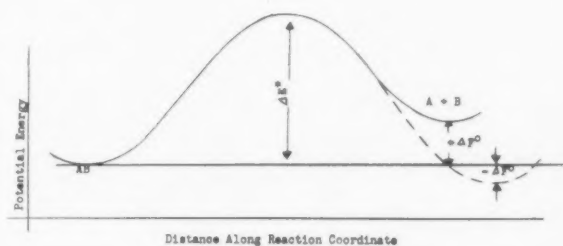
In terms of the standard enthalpy and entropy of activation, using

$$\Delta F^* = \Delta H^* - T \Delta S^*$$

it follows that

$$k = \frac{RT}{Nh} e^{\Delta S^*/R} e^{-\Delta H^*/RT} \quad [3]$$

FIG. 1 — Potential energy diagram of the photodecomposition of a molecule  $AB$  to the products  $A + B$ .



Immediately following the reaction, the products are in an excited energy state. It is possible to trap the products in this state, in certain instances, with the aid of very low temperatures and rigid (frozen) solvents.<sup>8</sup> It is unlikely that such techniques will be of any practical significance in solar energy work, at least within the foreseeable future. Under more usual conditions, the activated products will dissipate the energy of activation by means of collision and other mechanisms and revert to the ground state. It follows, therefore, that under the usual conditions a significant fraction of the activation energy supplied by the photon is inevitably lost. The net energy change and, hence, the recoverable energy, is measured in terms of the standard free energy of the reaction,  $\Delta F^\circ$ , where the reactants and the products are regarded as existing in an arbitrarily defined, or standard, ground state. If  $\Delta F^\circ$  is positive, the products possess greater energy (chemical) in the standard state than the original reactants; i.e., there has been a net uptake of energy as a result of the reaction. Such endothermic reactions are of prime interest in solar energy conversion. On the other hand, the great majority of photochemical reactions, unfortunately, are exothermic; that is, they exhibit a decrease in free energy and so are of no interest. The situation with respect to free energy change has been indicated schematically in Fig. 1.

### FACTORS AFFECTING SOLAR ENERGY CONVERSION

It is apparent from the previous discussion that a great number of factors can influence a photochemical reaction. Meaningful data and reproducible performance can be assured only after a careful study of a number of variables and their interactions. Some of the major factors will now be discussed.

#### (a) Spectral Quality and Intensity

As indicated earlier, in order for a photochemical reaction to occur, the incident light must be of a frequency which will be absorbed by the molecule and produce activation. The majority of endothermic photochemical reactions, (see Ref. 9, Table II, modified after Calvert) require ultraviolet light for activation. As can be seen from the solar spectrum, reproduced in Fig. 2,<sup>10</sup> only a small frac-

FIG. 2 — Spectral distribution of sunlight arriving at earth's surface.

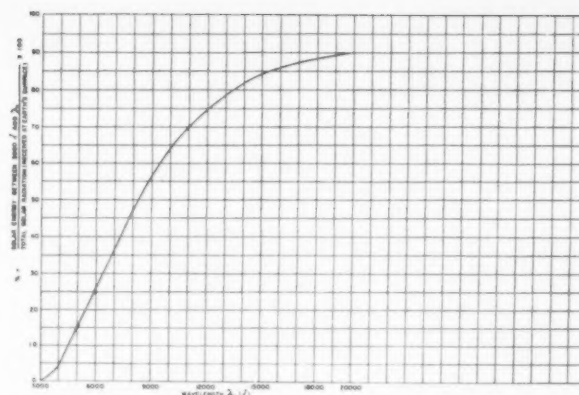
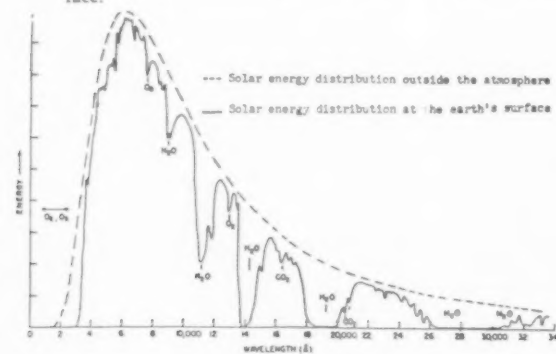


FIG. 3 — Fractional solar energy corresponding to various wavelengths.

tion of the solar spectrum lies in the ultraviolet. A plot of the fractional solar energy corresponding to various wavelengths is given in Fig. 3, where it can be seen that the ultraviolet portion, *in toto*, amounts to about only 4 per cent of the incident solar energy. The shortest wavelength in the solar ultraviolet is about 3000Å, so that reactions requiring shorter wavelengths will not take place to any significant extent.

It is apparent from Table II that several of the reactions which proceed at 4000Å or less possess a large  $\Delta F^\circ$  and a relatively high quantum yield. However, as indicated above, only a small portion of the solar spectra is utilized; and the ultimate utility of these reactions will depend on whether appropriate catalyst and sensitizers can be discovered which will extend the action spectra to longer wavelengths. Some of the more pertinent work with sensitizers and catalyst will be discussed below.

The solar spectrum shown in Fig. 2<sup>10</sup> gives the relative intensity of the radiation both outside of the atmosphere and at the earth's surface. The strong absorption bands (at the longer wavelengths) are due to water and CO<sub>2</sub>. Absorption of oxygen and ozone account for the removal of wavelengths shorter than 3000Å in the ultraviolet region of the spectra. Variations in the distance and position of the sun, atmospheric water, dust, etc., will influence the spectra. A valuable and detailed discussion of these factors has been given by P. Moon.<sup>11</sup>

The rate of the photochemical reaction at some wavelengths can be calculated if the Beer-Lambert expression holds:

$$I_{abs} = I_0 (1 - e^{-Kcl}) \quad [4]$$

The amount of radiant energy absorbed,  $I_{abs}$ , is not given by this simple expression if, for example, the absorbing species undergoes association or aggregation, accompanying changes in concentration or pressure, to produce a second species which also absorbs in the same spectral region. The rate at which the reaction products are produced is given by the expression:

$$\text{rate} = I_{abs} \phi_\lambda \quad [5]$$

where  $\phi_\lambda$  is the quantum yield of the product at wavelength  $\lambda$ . If the light is not monochromatic, but is con-



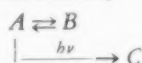
tained within the wavelengths  $\lambda_1$  to  $\lambda_2$ , a mean quantum yield  $\bar{\phi}$  may be defined by

$$\bar{\phi} = \frac{\int_{\lambda_1}^{\lambda_2} I_{0\lambda} (1 - e^{-K\lambda d}) \phi_{\lambda} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{0\lambda} (1 - e^{-K\lambda d}) d\lambda} \quad [6]$$

and the rate can be expressed as

$$\text{rate} = I_{0\lambda} \bar{\phi}$$

In certain instances, the intensity of illumination can influence the relative proportion of the products. A simple example is provided by the scheme,



In this scheme,  $A$  undergoes reversible thermal activation to  $B$  and photoactivation to  $C$ . Consequently, as the intensity of illumination increases, the ratio of  $C$  to  $B$  will increase. A number of considerably more complicated mechanisms can occur in practice.

### (b) Vessel Geometry and Wall Effects

Certain photochemical reactions carried out in the gaseous phase are sensitive to the shape of the containing vessel and the nature of the inner walls. Increasing the surface volume ratio or reducing the pressure will tend, in general, to decrease the rate of such reactions. Effects such as these are attributable to the diffusion of atoms or free radicals to the walls of the vessel when they are absorbed or recombined. The mean free path  $d$  of a molecule in a gaseous phase is given by the expression

$$d = \frac{RT}{\pi \sigma_m^2 N p \sqrt{2}} \quad [7]$$

If the pressure is such that the mean free path of an active species is comparable to the dimension of the containing vessel, then appreciable diffusion to the walls will occur. An example of a reaction which is sensitive to the nature of the containing vessel is the previously mentioned photochemical reaction between  $H_2$  and  $Cl_2$ . The active species  $H$  and  $Cl$  atoms which are responsible for the propagation of the chain can be absorbed by the walls and effectively eliminated.

The efficiency with which the walls promote adsorption and recombination depends on the chemical and physical properties of the surface. Taylor and Lavin,<sup>12</sup> for example, reported that coating a vessel with  $KCl$  increases the recombination reaction  $H + OH \rightarrow H_2O$ . The mechanisms of surface reactions, though intensively studied, are not well understood.

It should be emphasized that chain reactions, such as those discussed above, are exothermic and so are of little interest in solar energy work. They do, however, provide well-studied examples of the variety of effects which can influence photochemical reactions. (A recent discussion of chain reactions is given in Ref. 13.)

### (c) Impurities, Sensitizers, and Inhibitors

Photochemical reactions may be influenced to a very great extent by the addition of relatively small amounts of certain materials. Impurities which absorb in the same region as the reactant reduce the effective intensity of the radiation. Side reactions with impurities may give rise to new products and also reduce the relative yield of the desired product. A number of such effects can occur and considerable attention must be given to the chemical purity of the system. The presence of certain materials may serve to inhibit or greatly retard a photochemical reaction. Small amounts of  $NOCl$  will greatly retard the photosynthesis of phosgene from  $CO$  and  $Cl_2$ .<sup>14</sup> Inhibitors act by combining with active centers or dissociating into products which do so.

Perhaps the most useful and interesting effect which can be achieved with additives is that provided by photosensitizers. Photosensitizers permit a photochemical reaction to occur at wavelengths at which it ordinarily does not take place. These substances act by absorbing photons in the sensitizing region of the spectrum and then transferring the resultant excitation energy to the reactants. The mechanism of the energy transfer may involve a collision-type mechanism or, possibly, an inductive resonance-type process.<sup>15</sup> A classic example of photosensitization is provided by the photodehydrogenation of propane by mercury. Mercury ( $^1S_0$ ) will absorb photons at 2357 Å and the activated atoms,  $Hg$  ( $3P_1$ ), can then bring about the conversion to propane, hydrogen, hexane, as well as other products depending on temperature, pressure, etc. The field of photography provides an interesting example of photosensitization in the solid state. Silver bromide shows no response to radiations of wavelengths greater than 5000 Å. However, the addition of cyanine as well as other types of organic dyestuffs permits latent image formation in the red and, indeed, in the infrared to about 1200 Å.<sup>16</sup>

### (d) Temperature

As might be expected, the changes in temperature can influence a photochemical reaction in a number of ways. The nature and yield of the primary reaction may change with temperature. As indicated earlier, the essential condition for a photochemical reaction is that the thermal energy of the molecule together with the energy imparted by the photon can be equal or greater than the activation energy. Increasing the temperature will increase the vibrational energy of a molecule so that the contribution of the photon may be less; i.e., photons of longer wavelengths will be capable of activating the molecule. Chlorine, for example, will not decompose at 5000 Å until the temperature is raised to 100°C.

Changes in temperature can result in a number of other effects. The absorption peak is frequently broadened and shifted toward longer wavelengths.<sup>17</sup> The rates of thermally activated side reactions may be expected to increase, as indicated in Equation [2]. The resultant of such effects may be quite complex and difficult to predict beforehand.

## EFFICIENCY OF PHOTOCHEMICAL REACTIONS

The efficiency of a photochemical reaction is defined as the fraction of the incident radiation converted to chemical energy. One measure of the theoretical efficiency of a photochemical reaction is that suggested by Calvert<sup>9</sup> and used to calculate the value listed in Table II. Calvert defines the efficiency,  $Q$ , as

$$Q = 100 \Delta F^\circ \phi_A / E_\lambda \quad [8]$$

where  $\Delta F^\circ$  is the standard free energy in kcal per mole for some product  $A$ ;  $E_\lambda$  is the kcal per einstein of radiation of wavelength  $\lambda$ , calculated from Equation 1; and  $\phi_A$  is the quantum yield of the product  $A$ . This expression gives the percentage of the radiant energy converted if all of the energy at wavelength  $\lambda$  were absorbed and all of the resulting product recovered.

In practice, the incident energy is not monochromatic but rather extends over a wavelength region  $\lambda_1$  to  $\lambda_2$  of the solar spectra. Moreover, the absorption will not be complete, and the coefficient  $K$  will vary with wavelength as will, in general, the quantum yield  $\phi_\lambda$ . A more realistic expression for the theoretical fractional efficiency taking all of these considerations into account and assuming that the Beer-Lambert law holds is

$$\eta_t = \frac{\Delta F^\circ}{2.86 \times 10^5} \int_{\lambda_1}^{\lambda_2} \phi_\lambda (1 - e^{-Kc}) \lambda d\lambda \quad [9]$$

This, then, is the efficiency over the entire spectrum assuming that all of the product is recoverable. If  $\phi_\lambda$  remains essentially constant, and if the absorption is nearly complete over the entire spectrum, then the above expression reduces to

$$\eta_t = \frac{\Delta F^\circ \phi_\lambda}{2.86 \times 10^5} \left( \frac{\lambda_2^2 - \lambda_1^2}{2} \right) \quad [10]$$

Recovery of the product is not complete in practice because of mechanical difficulties as well as inefficiencies, such as reverse and side reactions, inherent in the kinetics. The practical functional efficiency,  $\eta_p$ , will then be characterized by a recovery factor,  $R$ , less than unity:

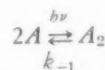
$$\eta_p = R \eta_t \quad [11]$$

The quantities  $\eta_t$  and  $\eta_p$ , not now in general use, provide an unambiguous technique for the intercomparison of various photochemical reactions with respect to their utility in solar energy work.

Equations [10] and [11] make clear some of the criteria for judging a photochemical reaction. Ideally, a reaction should have a reaction spectra which extends over the visible and ultraviolet and should proceed with a large positive free energy change with a quantum yield approaching unity. These conditions imply that the various deactivation and side reactions occur only to a minor extent and that the products do not absorb in the spectral region utilized by the primary reaction.

In addition, the products must be recoverable in good yield. Ease of recovery of the products will depend among other things on their physical properties and the rate of reverse and side reactions. A simple illustration of the

various factors at play is provided by the dimerization of anthracene in the presence of ultraviolet radiation and the reverse thermally activated reaction which proceeds in the dark. This type of reaction may be represented by the equation



and it follows that

$$\frac{d(A)}{dt} = -Iab\phi_{A_2} + (k_{-1})(A_2)$$

When equilibrium is achieved (the photostationary state) the concentrations will remain constant and that of the product will be given by

$$(A_2) = \frac{Iab\phi_{A_2}}{k_{-1}}$$

If the rate of the reverse reaction is large, not only will the concentration of the product be small in the photostationary state, but, in addition, the state will be approached rapidly. However, if the products are insoluble or can be, in some way, removed at a sufficiently rapid rate, then the photostationary state will not be realized, and high efficiencies may be achieved. Such considerations as these require that full attention be given to the selection of solvents, the use of precipitating agents, and complexing agents, as well as specific adsorbents in the development of a photochemical system.

The utility of the stored chemical energy will depend on the rate at which heat is released as well as the temperature achieved in the reverse reaction. As is well-known, the thermodynamic efficiency increases with increasing temperature of the heat source. If  $\Delta H^\circ$  is the standard enthalpy per mole of the reverse product and  $k_{-1}$  is the rate of the reverse reaction, the  $\Delta H^\circ / k_{-1}$  is a measure of the rate of heat production during recovery. A high rate of heat production requires, then, that the product be large, and this condition frequently implies that an appropriate catalyst be available.

Finally, in addition to the above kinetic and photochemical considerations, the utility of a system must be judged in terms of the traditional engineering standards such as the costs and availability of reactants, corrosion and storage problems, toxicity, and other hazards.

## DISCUSSION OF SOME SPECIFIC REACTIONS

Calvert<sup>9</sup> has made a study of the photochemical reactions which appeared to hold some promise and has summarized the progress of research in this field up to the year 1952. The present investigation has not uncovered any new photochemical reactions which were not considered by Calvert, although some progress has been made since 1952 with several of the reactions which were considered promising at that time. Table II presents the adsorption ranges, quantum yields, and free energy changes involved in a number of near ultraviolet and visible photochemical reactions which are of the most interest in terms of utilization of the solar energy. It is based on the compilation made by Calvert, which has been slightly modified to reflect recent progress.

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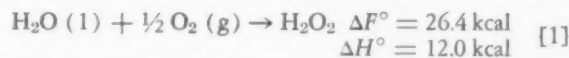
TABLE II  
NEAR ULTRAVIOLET AND VISIBLE PHOTOCHEMICAL REACTIONS

Over-all chemical reaction	Effective wavelengths Å	Quantum yield (product)	$\Delta F^\circ$ 298 kcal/mole	Per cent efficiency	Reference
(1) $\text{H Br} \rightarrow \frac{1}{2} \text{Br}_2 + \frac{1}{2} \text{H}_2$	<2537 2090	1.0 ( $\text{Br}_2$ ) 1.0	12.5	22.2 18.3	18
(2) $\text{SO}_2 \rightarrow \frac{1}{2} \text{O}_2 + \text{SO}$	<2760	(small)	16.2		19
(3) $\text{COCl}_2 \rightarrow \text{CO} + \text{Cl}_2$	<2750 2537	0.9 ( $\text{CO}$ )	16.3	14.0 13.1	20
(4) $\text{NO}^-_2 \rightarrow \text{NO}^- + \frac{1}{2} \text{O}_2$ (water solution)	<3350 2804 2700 2540	0.014 ( $\text{NO}^-_2$ ) 0.024 0.07 0.30	18.0	0.20 0.42 1.2 4.8	21 22
(5) $\text{NO}_2 \rightarrow \text{NO} + \frac{1}{2} \text{O}_2$	<4350 4050 3660	0.0092 ( $\text{NO}$ ) 0.0072 1.54	9.0	0.13 0.09 17.6	23
(6) $\text{NOCl} \rightarrow \text{NO} + \frac{1}{2} \text{Cl}_2$	<6370 3650	2.0 ( $\text{NO}$ ) 2.0	4.9	21.8 12.5	24 25
(7) $2 \text{Fe}^{+2} + \text{I}^-_2 \rightarrow 2 \text{Fe}^{+3} + 2 \text{I}^-$ (water solution)	<5460 3660	2.0 ( $\text{Fe}^{+3}$ )	9.4	9.0 6.0	26
(8) $\text{I}_2 + \text{NO}^-_2 + \text{H}_2\text{O} \rightarrow \text{NO}^-_2 + 2 \text{HI}$ (water solution)	<5790 4360	0.1 ( $\text{NO}^-_2$ )	13.8	2.1	27
(9) $\text{Fe}^{+2} + \text{H}_2\text{O} \rightarrow \frac{1}{2} \text{H}_2 + \text{Fe}^{+3} + \text{OH}^-$ (water solution)	<2900	0.19 ( $\text{H}_2$ )	36.2	14.1	28
(10) 2 Anthracene $\rightarrow$ Dianthracene (organic solution)	<3800 3660 3130	0.25 ( $\text{Dian.}$ ) 0.23	15.6 ( $\Delta H^\circ_{298}$ )	5.0 3.9	29
(11a) $\text{AgCl (s)} \rightarrow \text{Ag (s)} + \frac{1}{2} \text{Cl}_2$	<4050	1.0 ( $\text{Ag}$ )	26.2	37.1	30, 31
(11b) $\text{AgBr (s)} \rightarrow \text{Ag (s)} + \frac{1}{2} \text{Br}_2$	<4600	1.0 ( $\text{Ag}$ )	22.9	37.0	32
(11c) $\text{AgI (s)} \rightarrow \text{Ag (s)} + \frac{1}{2} \text{I}_2$	<4400	1.0 ( $\text{Ag}$ )	15.8	24.3	33
(12) $\text{H}_2\text{O} + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}_2$ (water suspension of $\text{ZnO}$ )	<4000 ~3000	0.5	25	13.1	34
(13) $\text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2$ ( $\text{Ce}^{+3}$ and $\text{Ce}^{+4}$ in $\text{HClO}_4$ solution)	2537 2537	0.0013 ( $\text{H}_2$ ) 0.15 ( $\text{O}_2$ )	54.5	0.06 7.3	35 36

Reactions [1], [2], [3], [4], [9], and [10] proceed only in ultraviolet light. Since, as mentioned previously, this region constitutes only a minor portion of the energy of the sun's radiation, sensitization of these reactions to longer wavelength radiation is a prerequisite to their consideration for the utilization of the solar energy. Nitrogen dioxide absorbs radiation up to wavelengths of 6000Å, but the activation energy for the decomposition process is so high that quanta with wavelengths greater than 3700Å do not possess sufficient energy to cause the reaction to proceed. For this reaction to receive any serious consideration, a reduction of the required activation energy through the use of a catalyst is necessary to enable the reaction to proceed at the longer wavelengths. Reactions [7] and [8] satisfy some of our requirements. However, they present problems with regard to the separation of the products from the reactants which is necessary in order to avoid a photostationary state. Reactions [11a], [11b], and [11c] are presented as examples of heterogeneous reactions involving solids. The nature of the reactants and the products makes them unsuitable for large-scale utilization of the solar energy. Reactions [6], [12], and [13] may be sufficiently promising to warrant a more detailed discussion in this paper.

#### PHOTOCHEMICAL HYDROGEN PEROXIDE SYNTHESIS

One of the more promising reactions for the photochemical conversion and storage of solar energy is the formation of hydrogen peroxide from water and oxygen. The over-all reaction is:

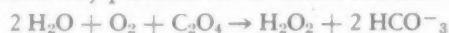


Experimentally, it has been found that neither water nor oxygen absorb to any extent in the visible or near ultraviolet regions; therefore, the reaction will not proceed in sunlight without assistance. This assistance must come from a sensitizer that does absorb in the visible and near ultraviolet and can thereby bring about the reactions at these shorter wavelengths.

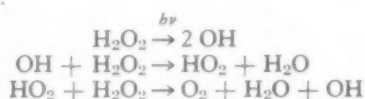
Much work has been done on the formation of hydrogen peroxide from water in the presence of oxygen using zinc oxide as a sensitizer. Chari and Qureshi<sup>38</sup> found that in the presence of zinc oxide water was oxidized to hydrogen peroxide on absorption of near ultraviolet radiation. The zinc oxide may function both as a sensitizer to near ultraviolet radiation and as a surface catalyst which reduces the free energy of activation required for the reaction. Since the reverse reaction (the photodecomposition of hydrogen peroxide) proceeds at wavelengths less than 4000Å, phenol must be added as an inhibitor when working in this range. Chari and Qureshi found that the rate of hydrogen peroxide production increased with increasing concentrations of zinc oxide up to a certain optimum concentration, beyond which further additions had no effect. Yields of hydrogen peroxide were also observed to increase with increasing pH.

Rubin, Calvert, Rankin, and MacNevin<sup>39</sup> have studied the effect of the wavelength of the incident light on the quantum yield of hydrogen peroxide for the zinc oxide system. They found a constant quantum yield of almost 0.5 in the region 2500-3500Å which fell off rapidly as

4000Å was approached, due to the insensitivity of zinc oxide to wavelengths above this value. These investigators also studied the action of sodium oxalate and formate as inhibitors, finding the latter more effective. Increasing the concentrations of sodium formate from 0.1 to 0.5M resulted in an increase in quantum yield of 0.37 to 0.51. They have advanced the theory that organic additives do not inhibit the reverse reaction, but rather that some hydrogen peroxide is formed through photochemical oxidation of the organic stabilizers themselves. The mechanism which they postulate for an oxalate stabilizer is



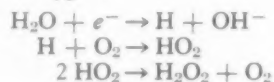
Other investigators, however, feel that organic stabilizers function as inhibitors by reacting with free radical intermediates formed during hydrogen peroxide decomposition. The decomposition of  $\text{H}_2\text{O}_2$  is postulated to occur as follows:



Organic stabilizers may break this chain by reaction with the hydroxyl radical:



The mechanism of the formation of hydrogen peroxide at zinc oxide surfaces is another subject involving conflicting reviews. Markham and Laidler<sup>40</sup> suggested that the initial step in the mechanism involves the photoactivation of a zinc oxide by a quantum of absorbed light energy. Since zinc oxide has the properties of a semiconductor, they theorize that the mechanism proceeds with a transfer of a photoexcited electron from the zinc oxide to an adsorbed water molecule, causing it to dissociate into a hydroxyl ion and a hydrogen atom. A subsequent reaction occurs between a hydrogen atom and oxygen, forming  $\text{HO}_2$ . This is followed by a reaction between two  $\text{HO}_2$  molecules to form hydrogen peroxide and a molecule of oxygen:



Calvert, Theurer, Rankin, and MacNevin<sup>41</sup> designed experiments to determine the origin of the oxygen in the hydrogen peroxide. Using  $\text{O}^{18}$  they demonstrated conclusively that the oxygen in the hydrogen peroxide came entirely from the oxygen gas and not from the water, zinc oxide, or stabilizer. These investigators suggest that the primary step, after photoactivation of a zinc oxide molecule, is a reduction of a molecule of oxygen adsorbed on the zinc oxide surface by a photoexcited electron:



Studies have also been made of the efficiencies of other surface catalysts in sensitizing the reaction of water and oxygen to produce hydrogen peroxide. Chari and Qureshi, in a later paper,<sup>42</sup> compared the efficiencies of zinc carbonate and zinc oxide in promoting the reaction. They found wide variations in the quantum yields obtained with each, depending on the method of preparation. The

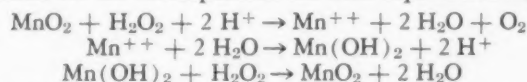
method of preparation of most surface catalysts is known to influence their efficiencies. In general, higher yields of hydrogen peroxide formation were obtained with zinc carbonate than with zinc oxide. Stevens, Ke, and Trivich<sup>43</sup> evaluated the efficiencies of a number of surface catalysts including zinc oxide, cadmium sulfide, mercuric sulfide, cadmium selenide, and zinc sulfide. These experiments indicated that under comparable conditions, the highest hydrogen peroxide yield was obtained using cadmium sulfide precipitated from cadmium chloride solutions. Aside from being the most efficient catalyst, cadmium sulfide may be able to extend the range of wavelengths which promote the reaction since yellow and red cadmium sulfide absorb to 5200Å and 5800Å respectively. Unfortunately, results were reported in terms of concentration of hydrogen peroxide produced rather than in quantum yields. However, some idea of the relative efficiency of cadmium sulfide may be obtained by comparing resultant hydrogen peroxide concentrations with those obtained under identical conditions with zinc oxide. Concentrations obtained using cadmium sulfide at 3650Å were 20 per cent greater than those obtained with zinc oxide. In the range 3650-4360Å, concentrations of hydrogen peroxide obtained with cadmium sulfide were equally as high as those obtained at 3650Å and did not decline appreciably until 5460Å was approached. In contrast, concentrations of hydrogen peroxide obtained with zinc oxide dropped 93 per cent in going from 3650Å to 4050Å.

Grossweiner<sup>44</sup> has studied the factors affecting hydrogen peroxide formation in mercuric sulfide systems. He found that, if successive samples of pure water are mixed with 1 gm of  $\text{HgS}$  and then irradiated, the total accumulated yield is a linear function of the accumulated radiation time. The catalyst does not seem to undergo any permanent change, nor does it seem to be poisoned by the reaction. Of course, these were rather short runs, and long-range effects cannot be excluded. The gas used in the system has a marked effect on the reaction. If the solution is saturated with helium and irradiated for one hour, the yield is 3.1  $\mu\text{m}/1$  (micro moles per liter) of  $\text{H}_2\text{O}_2$ . Under the same conditions, air yields 13.8  $\mu\text{m}/1$  and oxygen 22.6  $\mu\text{m}/1$ . The fact that a yield of  $\text{H}_2\text{O}_2$  was obtained with helium may be due to either some absorbed oxygen or some mechanism not requiring oxygen. Like Chari and Qureshi, Grossweiner also found that the hydrogen peroxide yield increased with increasing pH. Although Stevens, Ke, and Trivich reported that cadmium sulfide was about three times as efficient as mercuric sulfide in producing hydrogen peroxide in the ultraviolet region, it was found that the situation is reversed in the visible portion of the spectrum where mercuric sulfide absorbs strongly. The mercuric sulfide system absorbs light energy up to above 7500Å and has a peak in peroxide formation at about 5000Å.

The release of the energy absorbed in the production of hydrogen peroxide requires a decomposition procedure that will be both rapid and quantitative. Such decomposition can be obtained by a thermal method; however, it has been found that the rate of decomposition is increased



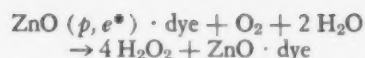
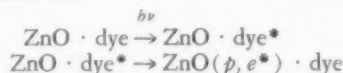
considerably by the use of inorganic catalysts. Some 32 inorganic catalysts have been reported.<sup>45</sup> In particular, the oxides of some heavy metals have been found to produce very active decomposition. A simple technique consists of spraying an aqueous solution of a permanganate salt into a decomposition chamber at the same time that the hydrogen peroxide solution is introduced. The permanganate ion interacts with  $\text{H}_2\text{O}_2$  and is reduced forming fine solid particles of manganese oxides. The mechanism for the decomposition has been represented as,



Exceptionally successful procedures have been developed for the decomposition of hydrogen peroxide by spraying peroxide over solid catalysts packed in beds. The speed of the reaction is apparent in that it is reported that 1 kgm of catalyst can decompose 150-200 gm of hydrogen peroxide per second. However, impurities in more than trace quantities will eventually reduce the activity of the catalyst. In short, it may be stated that the decomposition of hydrogen peroxide liberating the energy involved in its formation may be accomplished through the use of inorganic catalysts with excellent yields.

In the way of a summary, it may be stated that the photosynthesis of hydrogen peroxide has at present the serious drawback of very low yields. The reported concentrations of  $\text{H}_2\text{O}_2$  are in the neighborhood of micromoles per liter. The future utility of this reaction depends, obviously, on the development of more efficient sensitizers and catalysts as well as on the extent to which the longer wavelengths of the solar spectra can be utilized. Zinc oxide appears to be limited to 4000Å and less. Sensitizers such as cadmium and mercuric sulfides are a step in this direction, although, here again, the efficiencies are very low. On the other hand, the reaction possesses certain attractive features; namely, a large  $\Delta F^\circ$  and the low cost of readily available reactants. The reverse reaction which occurs below 4000Å can be minimized with the aid of inhibitors. However, if the reaction can be efficiently sensitized at longer wavelengths, this difficulty can be avoided by the use of ultraviolet filters.

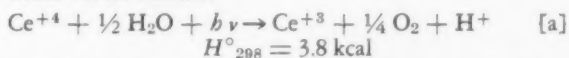
The possibility of utilizing organic dyes, akin to those employed in photography which absorb over the visible regions of the solar spectra, together with the above-mentioned inorganic sensitizers, may warrant some investigation. Investigations of photographic sensitization<sup>16</sup> indicates that such dyes can be adsorbed onto silver bromide and that the excitation energy of the adsorbed dye can be transferred to the silver bromide lattice with consequent excitation of the valency electron to higher energy states. As has been mentioned, it is generally believed that solid state sensitizers for  $\text{H}_2\text{O}_2$  production function by providing photoexcited electrons to the reactants, so that in the presence of an adsorbed dye, the following scheme may be postulated:



The asterisk indicates excitation energy which on transfer to the ZnO lattice results in promotion of an electron to a higher energy state,  $e^*$ , and the creation of a positive hole,  $p$ , in the valency band. Insofar as the reviewers are aware, such studies have not been reported.

## THE PHOTOCHEMICAL DECOMPOSITION OF WATER BY CERIUM IONS

The sensitized decomposition in the ultraviolet of water into hydrogen and oxygen by means of a perchloric acid solution of cerium ions holds some promise as a means of collecting and storing solar energy. The decomposition of aqueous solutions of ceric ion in the presence of sunlight was first reported by Bauer in 1908, but it is only within the last 10 years that it has been under serious investigation. The over-all reaction for the oxidation of water can be written:

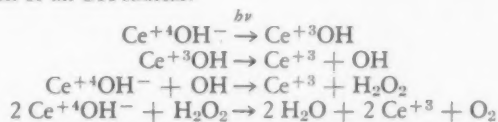


Heidt<sup>46,47,47</sup> has found the quantum efficiency of the photooxidation processes (defined as moles of ceric ion reduced to cerous ion per einstein of light absorbed by both ceric and cerous species) at 2537Å to be 0.15. He has not yet studied this reaction quantitatively at any other wavelength. He postulates the formation of a ceric dimer as the first step in the mechanism:

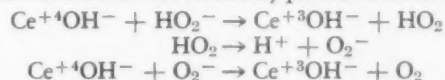
- (1)  $2 \text{Cm} \rightarrow \text{Cp}$
- (2)  $\text{Cp} + h\nu \rightarrow \text{Cp}^*$
- (3)  $\text{Cp}^* + \text{H}_2\text{O} \rightarrow 2 \text{C}_3 + 2 \text{H}^+ + \frac{1}{2} \text{O}_2$
- (4)  $\text{Cp}^* + \text{C}_3 \rightarrow \text{Cp} + \text{C}_3 + \text{heat}$
- (5)  $\text{Cp}^* + \text{S} \rightarrow \text{Cp} + \text{S} + \text{heat}$

$\text{Cm}$  represents all ceric monomers such as  $\text{CeOH}^{+3}$ ,  $\text{Ce}(\text{OH})_2^{+2}$ , etc.;  $\text{Cp}$  represents all ceric dimers which are in equilibrium with the monomers;  $\text{C}_3$  represents  $\text{Ce}^{+3}$ ;  $\text{S}$  represents any substance except  $\text{C}_3$ .

While dimerization could account for the kinetics, and various emf measurements point toward the existence of these dimers, there is no spectrographic evidence for the existence of this species in solution. As a result of this lack of spectrographic evidence, Evans and Uri<sup>48</sup> have postulated an alternate mechanism involving the production of an OH radical:



The last reaction in this series may proceed as follows:

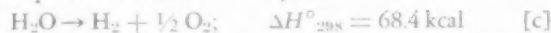


Thermal energy can also be used as a source of activation energy in the absence of light.

If a solution containing only cerous ion is irradiated with ultraviolet light, Heidt<sup>47,49</sup> found that the cerous is oxidized to ceric and that the water is reduced with the formation of hydrogen.



Combining reaction [a] and [b] for the photooxidation and photoreduction of water yields:



Thus, if a mixture of ceric and cerous perchlorates in perchloric acid solution is irradiated by light of 2537Å, hydrogen and oxygen are produced with an increase in enthalpy amounting to 68.4 kcal per mole. Unfortunately, the maximum quantum yields obtained thus far for the photoreduction of water are only 0.0013 at 2537Å. The quantum efficiency at other wavelengths has not been measured. When the system was exposed to sunlight, it produced only very small quantities of hydrogen and oxygen.

This system has a basic appeal in that it utilizes readily available materials, the over-all reaction is highly endothermic, and the products, hydrogen and oxygen, can be conveniently stored until required and then utilized in several different ways, depending on the form of energy required for the specific application. If direct conversion to heat is desired, the products can, of course, be burnt. Direct conversion to electricity is possible by means of the Bacon Cell.<sup>50</sup>

The Bacon Cell consists of two porous nickel diffusion electrodes 4 mm thick. On the gas side of each electrode, the pores are approximately 30  $\mu$  in diameter, while on the liquid side they are only 16  $\mu$  in diameter. A solution of 21 per cent KOH is circulated between the electrodes; since thermal cycling is used, no moving parts are necessary. A small pressure difference is set up across each electrode, so that the gas fills the large pores, but cannot bubble through the smaller pores on the liquid side. Oxygen molecules are adsorbed on the metal-oxide layer of the anode. This adsorbed gas layer is very active; it combines with water to form  $\text{OH}^-$  ions and removes electrons from the electrode in this process. At the cathode the adsorbed hydrogen reacts with hydroxyl ions to yield water and electrons:



Best results are achieved with the cell at 240°C and 800 lb per sq in. pressure.

J (milliamperes/cm <sup>2</sup> )	0	162	413	720	1067
V (volts)	1.05	0.9	0.8	0.7	0.6

Highest circuit voltage recorded was 1.096 at 200°C and 571 lb per sq in. pressure. The efficiency of these batteries varies from 54-67.5 per cent at voltages between 1.0 and 0.8. One of these cells had been running continuously for over 800 hours.

Recently, the National Carbon Company<sup>51</sup> has announced a very promising cell which utilizes porous carbon electrodes and KOH as the electrolyte. The cell operates at 120-140°F and at atmospheric pressures in comparison to the higher temperatures and pressures required for the Bacon Cell. Cell efficiencies are reported as falling between 65 to 85 per cent.

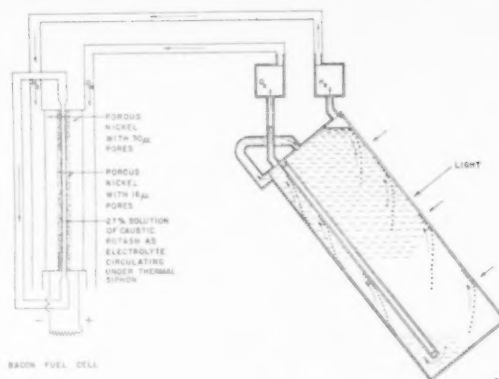


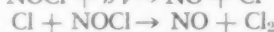
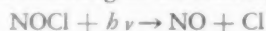
FIG. 4 — Apparatus for the production and separation of hydrogen and oxygen, used in conjunction with Bacon fuel cell to produce electricity.

Heidt<sup>52</sup> has published a design of an apparatus for the production and separation of oxygen and hydrogen by the simultaneous photooxidation and reduction of water by cerium ions. Fig. 4 shows how this apparatus can be used in conjunction with a Bacon Cell to produce electricity directly from the products of water photolysis.

It is seen that the photosensitized decomposition of water must undergo much further development if it is to find any economical application. As with the photosynthesis of  $\text{H}_2\text{O}_2$ , the efficiencies must be increased, and the action spectra extended into the longer wavelength regions. The very low quantum yield for  $\text{H}_2$  production is particularly discouraging.

## THE PHOTODECOMPOSITION OF NITROSYL CHLORIDE

The photodecomposition of nitrosyl chloride is a particularly attractive system from the standpoint of utilization of the solar energy, since nitrosyl chloride strongly adsorbs radiation between wavelengths 3650Å to 6400Å. Kistiakowsky<sup>53</sup> has investigated the photodecomposition of nitrosyl chloride at wavelengths ranging from 3650Å to 6350Å. In every case, quantum yields of two were obtained. In order to account for this observed quantum yield, two mechanisms were proposed. The first postulates the dissociation according to the scheme,

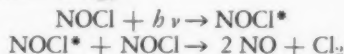


The over-all equation for the reaction is as follows:



The energy of activation required by this reaction is dependent primarily on the energy required for the first step in the chain reaction; i.e., it is a primary dissociation of nitrosyl chloride into nitric oxide and a chlorine atom. The minimal energy required for the initial step may be calculated from the heats of formation of nitrosyl chloride and nitric oxide and from the heat of dissociation of chlorine, and corresponds to 46.4 kcal per mole. This energy corresponds to 6200Å as the longest wavelengths

capable of decomposing NOCl. On the basis of such considerations as these, together with certain spectroscopic observations, a second mechanism was proposed which does not involve photodissociations as the primary act. The excited NOCl is considered as undergoing decomposition on collision with a second molecule possessing the requisite thermal energy:



The quantum yields reported by Kistiakowsky are initial quantum yields. At some constant experimental set of conditions, a point is reached at which there is a photostationary state produced involving definite concentrations of reactant and products due to an appreciable tendency for the reactants to recombine. Unless this equilibrium is distributed, the reaction will not proceed. The most logical way to suppress the reverse action is to separate the reaction products. A study is currently in progress at the University of Wisconsin to determine the efficiency of the separation effected by utilizing the differential solubility of the products in carbon tetrachloride which serves as the solvent for NOCl. Preliminary reports<sup>54</sup> indicate that over-all efficiencies are probably in the neighborhood of 10 per cent. A second shortcoming of this reaction is the relatively small free energy change associated with the reverse process.

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# CALCULATION OF THE CONCENTRATION OF ENERGY AT POINTS OUTSIDE THE FOCAL SPOT OF A PARABOLIC CONDENSER\*

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This paper is an analysis of the distribution of intensity and of energy falling outside of the circular projection of the cone of reflected radiation coming from all infinitesimal areas of the surface of a paraboloidal mirror. The method integrates the energy and intensity falling in the area swept by the major semi-axis of the ellipses subtended by the focal plane. The results are tabulated and graphed.

The energy collected by an infinitesimal area on the surface of the paraboloid mirror is spread in the focal plane over the area of an ellipse of semimajor axis  $R/\cos \theta$  and semiminor axis equal to  $R$ , where  $R$  is the radius of the base of cone of light whose axis makes an angle  $\theta$  with the axis of the paraboloid and whose center lies at the center of the focal spot. As the axis of the cone moves around the paraboloid at constant angle  $\theta$ , the major axis of the ellipse will rotate so that the energy collected by a ring of radius  $\rho \sin \theta$  and width  $\rho d\theta$ , where  $\rho$  is the distance from the ring to the focal spot of the paraboloid, is spread over a circle of radius  $R/\cos \theta$ .

Inside a circle of radius  $R$  the intensities add, being equal to

$$dI_c = \frac{e}{\pi R^2 / \cos \theta} 2 \pi \rho^2 \sin \theta d\theta \quad [1]$$

where  $dI_c$  represents the differential with respect to  $\theta$  of the intensity inside the circle of radius  $R$ , and  $e$  represents the solar constant. The energy spread over a circle of radius  $R$  is given by  $\pi R^2 dI_c$ , that is,

$$dE_c = 2 \pi e \rho^2 \sin \theta \cos \theta d\theta \quad [2]$$

But the total energy  $dE$  collected by the ring is given by

$$dE = 2 \pi e \rho^2 \sin \theta d\theta \quad [3]$$

leaving an amount of energy  $dE_r$  given by

$$dE_r = 2 \pi e \rho^2 \sin \theta (1 - \cos \theta) d\theta \quad [4]$$

to be spread over a ring in the focal plan of inner radius  $R$  and outer radius  $R/\cos \theta$ . This energy falls on an area  $A_r$  given by

$$A_r = (\pi R^2 / \cos^2 \theta) - \pi R^2 \quad [5]$$

Hence, the corresponding intensity  $dI_r$  is

$$dI_r = \frac{2 \pi e \rho^2 \sin \theta (1 - \cos \theta) \cos^2 \theta d\theta}{\pi R^2 \sin^2 \theta} \quad [6]$$

$$= \frac{2 e \rho^2 (1 - \cos \theta) \cos^2 \theta d\theta}{R^2 \sin \theta} \quad [7]$$

Substituting for  $R$  its value  $\rho a/2$ , where  $a$  is the angular diameter of the sun, we have

$$dI_c = (8 e/a^2) \sin \theta \cos \theta d\theta \quad [8]$$

$$dI_r = \frac{(8 e/a^2) (1 - \cos \theta) \cos^2 \theta d\theta}{\sin \theta} \quad [9]$$

If now we choose a circle in the focal plane of radius  $R$ , where  $R > R_a$ , the radius of the focal spot, up to a certain angle  $\theta_2$  given by  $R_2 = r$ , all the circles of radius  $R < r$  will lie within the circle of radius  $r$ , while all the circles such that  $R > r$  will lie without the circle of radius  $r$ . For the radius  $R_2$  we have

$$R_2 = 2 R_a / (1 + \cos \theta_2) = r \quad [10]$$

whence

$$\cos \theta_2 = (2 R_a / r) - 1 \quad [11]$$

The outer radius  $R_3$  of the ring over which the energy  $dE_r$  is distributed is given by

$$R_3 / \cos \theta_3 = 2 R_a / (1 + \cos \theta_3) \cos \theta_3 = r \quad [12]$$

so that

$$\cos \theta_3 = \left\{ \frac{-1 + \sqrt{1 + 8 R_a / r}}{2} \right\} \quad [13]$$

Now provided that  $r < R_1$ , where  $R_1$  is the radius of the base of the cone of light corresponding to the maximum value  $\theta_1$  of the paraboloid, we have as the resulting intensity  $I_r$  inside a circle of radius  $r$ :

$$I_r = (8 e/a^2) \int_{\theta_3}^{\theta_1} \sin \theta \cos \theta d\theta \quad [14]$$

$$+ (8 e/a^2) \int_{\theta_3}^{\theta_2} \frac{(1 - \cos \theta) \cos^2 \theta d\theta}{\sin \theta}$$

$$\text{while if } R_1 < r < R_1 / \cos \theta_1 \quad [15]$$

\*Originally issued as Holloman Air Development Center, Technical Memorandum No. HDGR-57-9, August 18, 1957.



$$I_r = 8e/a^2 \int_{\theta_3}^{\theta_1} \frac{(1 - \cos \theta) \cos^2 \theta d\theta}{\sin \theta}$$

while if  $r \geq R_1/\cos \theta_1$ , the resulting intensity is zero.

The resulting functions can all be easily integrated. We have for  $R_a < r < R_1$

$$I = (8e/a^2) [\cos \theta_2 - \log_e (1 + \cos \theta_2) + (\sin^2 \theta_1)/2 - \cos \theta_3 + \log_e (1 + \cos \theta_3) - (\sin^2 \theta_3)/2] \quad [16]$$

while for  $R_1 < r < R_1/\cos \theta_1$

$$I = (8e/a^2) [\cos \theta_1 - \log_e (1 + \cos \theta_1) + (\sin^2 \theta_1)/2 - \cos \theta_3 + \log_e (1 + \cos \theta_3) - (\sin^2 \theta_3)/2] \quad [17]$$

while finally for  $r > R_1/\cos \theta_1$ , we have  $I = 0$ .

It is of interest to calculate the values of  $\theta_2$  and  $\theta_3$  for various special cases.

Firstly, for  $r = R_a$ , we have  $\theta_2 = \theta_3 = 0$ , so that for this case we have the result

$$I = (8e/a^2) (\sin^2 \theta_1)/2$$

which is the result given by Bliss<sup>1</sup> for the intensity in the focal spot.

Secondly, for  $r = R_1$ ,  $\theta_2 = \theta_1$ , or for  $\theta_1 = 60^\circ$ ,  $r = (4/3) R_a$ .

Thirdly, for  $r = R_1/\cos \theta_1$ ,  $\theta_3 = \theta_1$ , when  $I = 0$ . For  $\theta_1 = 60^\circ$ , this corresponds to a value of  $r/R_a$  of 2.67.

The values of  $\cos \theta_2$ ,  $\log_e (1 + \cos \theta_2)$ ,  $\cos \theta_3$ ,  $\log_e (1 + \cos \theta_3)$ , and  $(\sin^2 \theta_3)/2$  were calculated and are given in Table I.

TABLE I

$r/R_a$	$\cos \theta_2$	$\log (1 + \cos \theta_2)$	$\cos \theta_3$	$\log (1 + \cos \theta_3)$	$1/2 \sin^2 \theta_3$
1.0	1.0000	0.6931	1.0000	0.6931	0.0000
1.1	0.8182	.5978	0.9382	.6618	.0599
1.2	.6667	.5108	.8816	.6321	.1114
1.3	.5385	.4308	.8346	.6068	.1516
1.4			.7930	.5839	.1856
1.5			.7558	.5629	.2143
1.6			.7248	.5451	.2374
1.7			.6920	.5259	.2606
1.8			.6644	.5095	.2793
1.9			.6392	.4942	.2957
2.0			.6180	.4812	.3091
2.2			.5747	.4541	.3348
2.4			.5389	.4311	.3547
2.67			.5000	.4055	.3750

The results given in Table I were combined to give the quantities in brackets in Equations [16] or [17] depending on the value of  $r/R_a$  and are given in the second column of Table II. The quantities in the second column were divided by 0.375 to obtain the ratio  $I/I_a$  given in the third column. To obtain the ratio of the total energy  $E$  falling within the circle of radius  $r$  to the energy  $E_a$  falling within the focal spot, it was noted that this quantity is given by the equation

$$E/E_a = \sum \frac{2\pi r_m (I_i + I_{i+1}) \Delta r}{\pi R_a^2 2 I_a} \quad [18]$$

where  $r_m$  is the mean radius of a ring of inner radius  $r_i$  and outer radius  $r_{i+1}$  and thickness  $\Delta r$ . This reduces to equation

$$E/E_a = \sum \frac{r_m}{R_a} \left( \frac{I_i}{I_a} + \frac{I_{i+1}}{I_a} \right) \frac{\Delta r}{R_a} \quad [19]$$

From this equation the values in the fourth column of Table II were calculated.

TABLE II

$r/R_a$	$\Sigma$	$I/I_a$	$E/E_a$
1.0	0.3750	1.0000	1.0000
1.1	.2591	0.6909	1.1175
1.2	.1700	.4533	1.3091
1.3	.1033	.2755	1.4002
1.4	.0748	.1995	1.4643
1.5	.0623	.1661	1.5173
1.6	.0524	.1397	1.5647
1.7	.0428	.1141	1.6066
1.8	.0353	.09413	1.6430
1.9	.0288	.07680	1.6746
2.0	.0236	.06293	1.7018
2.2	.0141	.03760	1.7440
2.4	.0070	.01867	1.7699
2.67	.0000	.0000	1.7827

Needless to say, these values are obtained on the basis of a uniform sun.

The values of  $I/I_a$  and  $E/E_a$  as a function of  $r/R_a$  have been plotted in Figs. 1 and 2.

Finally, it is of interest to compute the fractional part of the total energy concentrated in the focal spot and compare it with the result given in Table II. We have as the energy  $dE$  collected by a ring of radius  $\rho \sin \theta$  and width  $\rho d\theta$  at an angle  $\theta$  with the axis

$$dE = e 2 \pi \rho^2 \sin \theta d\theta \quad [20]$$

And as the total energy  $E$  collected by the paraboloid

FIG. 1 — Intensity as a function of distance from center of focal spot.

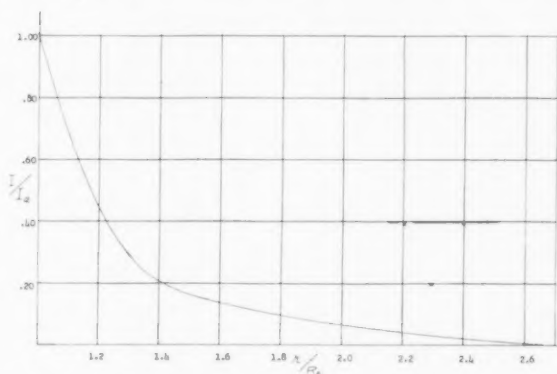
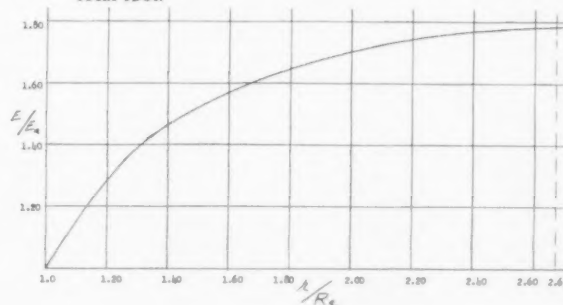


FIG. 2 — Total energy as a function of distance from center of focal spot.



$$E = \int_0^{\theta_1} e 2 \pi \rho^2 \sin \theta d\theta \quad [21]$$

Substituting for  $\rho$  its value  $2F/(1 + \cos \theta)$ , this becomes

$$E = \int_0^{\theta_1} \frac{8 \pi e F^2 \sin \theta d\theta}{(1 + \cos \theta)^2} \quad [22]$$

which gives for  $E$  the value

$$E = -\frac{4 \pi e F^2 (1 - \cos \theta_1)}{1 + \cos \theta_1} \quad [23]$$

For  $\theta_1 = 60^\circ$  this becomes

$$E = 4 \pi e^2 F^2 / 3 \quad [24]$$

For the focal spot we had as the intensity  $I$

$$I = (8 e / a^2) (\sin^2 \theta_1) / 2 \quad [25]$$

so that the total energy  $E_a$  collected by the focal spot is given by

$$E_a = \pi R_a^2 (8 e / a^2) (\sin^2 \theta_1) / 2 \quad [26]$$

Substituting in this expression for  $R_a$  its value  $F a/2$ , we have

$$E_a = \pi F^2 e \sin^2 \theta_1 \quad [27]$$

For  $\theta_1 = 60^\circ$  this becomes

$$E_a = \pi F^2 e 3/4 \quad [28]$$

so that we have for the ratio

$$E_a/E = \frac{3}{4} \times \frac{3}{4} = 9/16 = 56.3\%$$

Comparing this with the values given in Table II, namely

$$E_a/E = 1.000/1.7827 = 56.1\%$$

we see that the agreement is very good.

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# CALCULATION OF THE CONCENTRATION OF THE SOLAR RADIATION THROUGH THE FOCAL SPOT OF A PARABOLIC MIRROR\*

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This paper is an analysis of the power, or the energy per unit area per unit time, falling on the focal spot from a paraboloidal mirror. It is unique in that it takes account of the distribution of intensity over the solar disc as a function of wavelength. The results are compared with the work of two other men who used different assumptions.

## THE METHOD

The energy falling per square centimeter per minute on the focal spot of a parabolic mirror has been calculated by Bliss<sup>1</sup> for a uniform sun and by Jose<sup>2</sup> for a distribution curve of the intensity over the solar disc averaged for all the wavelengths. In the present report we shall take account of the fact that the distribution of intensity over the solar disc is a function of the wavelength.

Suppose we have given for a certain wavelength band first  $f(x)$ , where  $x$  is the ratio of the intensity  $I$  at a distance  $r$  from the center of the solar disc to the intensity  $I_0$  at the center of the solar disc, i.e., let

$$I/I_0 = f(x) \quad [1]$$

where

$$x = r/R_s \quad [2]$$

$R_s$  being the radius of the solar disc; and secondly, let  $e$  be the energy in calories per minute falling on one square centimeter of area normal to the direction of the sun for the given wavelength band.

Let  $R$  be the radius of the image of the solar disc formed in a plane which is perpendicular to the axis of the cone of light reflected from a projected area of one square centimeter. The power passing through this disc is  $e$  cal per sq cm per sec.  $I_0$  may be determined as a function of  $R$ ; we have

$$\begin{aligned} e &= \int_0^R I(r) ds = \int_0^{R_1} I(r) 2\pi r dr \\ &= \int_0^1 2\pi R^2 I_0 f(x) x dx \end{aligned} \quad [3]$$

so that

$$I_0 = e/2\pi R^2 \int_0^1 f(x) x dx \quad [4]$$

$$= e/2\pi R^2 S \quad [5]$$

where

$$S = \int_0^1 f(x) x dx \quad [6]$$

The focal spot of a solar furnace is considered to be the circular area in the focal plane which is produced by the sunlight which is reflected from the vertex of the parabolic condenser. The radius  $R_a$  of the spot is given by  $R_a = F\alpha/Z$ , where  $F$  is the focal length of the condenser and  $\alpha$  is the apparent angular diameter of the sun. The cone of light which is reflected from any point of zone angle  $\theta$  has the circular cross-sections

$$R = \frac{\rho\alpha}{2} = \frac{2F}{(1+\cos\theta)} \frac{\alpha}{2} = \frac{2R_a}{(1+\cos\theta)} \quad [7]$$

where  $\rho$  is the distance from the point on the paraboloid from which the light is reflected to the focal point, since it can be shown that

$$\rho = 2F/(1+\cos\theta) \quad [8]$$

In the vicinity of the focal plane, the reflected cone of light has a circular base of radius  $R$ . The flux through an elliptical area centered on the circular section of this cone is the part of the total flux which it passes through the focal area. This elliptical area is the projection of the focal spot on the circular section of the cone.

The semimajor axis  $a$  of the ellipse is  $R_a$ . The semiminor  $b$  is  $R_a \cos \theta$ . The energy passing through the ellipse is

$$E(\theta) = 4 \int_a^b I(r) r \phi(-dr) + \int_0^b I(r) 2\pi r dr \quad [9]$$

where

$$\phi = \arcsin \left\{ \cot \theta \sqrt{\frac{R^2(1+\cos\theta)^2}{4r^2} - 1} \right\} \quad [10]$$

Changing variables, we can write

\*Originally issued as Holloman Air Development Center, Technical Memorandum No. HDGR-57-10, August 15, 1957.

$$E(\theta) = -4 \int_{x_1}^{x_2} R^2 I_0 f(x) \phi(x) x dx \quad [11]$$

$$+ \int_0^{x_2} R^2 I_0 f(x) 2\pi x dx$$

where

$$\phi(x) = \arcsin \left\{ \cot \theta \sqrt{\left( \frac{1 + \cos \theta}{2x} \right)^2 - 1} \right\} \quad [12]$$

$$x_1 = a/R = (1 + \cos \theta)/2 \quad [13]$$

and

$$x_2 = b/R = (1 + \cos \theta)(\cos \theta)/2 \quad [14]$$

Substituting for  $I_0$  its value, we have

$$E(\theta) = -\frac{2e}{\pi S} \int_{x_1}^{x_2} f(x) \phi(x) x dx + \frac{e}{S} \int_0^{x_2} f(x) x dx$$

$$= E_1(\theta) + E_2(\theta) \quad [15]$$

$E(\theta)$  is the energy passing through the focal spot from light reflected at an angle  $\theta$  to the axis of the paraboloid per unit area of incident light projected on the paraboloid for the chosen wavelength band. The total energy  $dE(\theta)$  reflected at the angle  $\theta$  is proportional to the area of a ring of radius  $2\pi\rho\sin\theta$  and of width  $\rho d\theta$ , that is

$$dE(\theta) = E(\theta) 2\pi\rho^2 \sin\theta d\theta \quad [16]$$

so that the total energy  $E(\theta)$  over the whole paraboloid is given by

$$E(\theta) = 8\pi F^2 \int_0^{\theta_1} \frac{E(\theta) \sin\theta d\theta}{(1 + \cos\theta)^2} \quad [17]$$

where  $\theta_1$  is the angle of opening of the paraboloid.

The concentration  $c(\lambda)$  is the total energy passing through the focal spot divided by the area of the focal spot, so that we have

$$c(\lambda) = \frac{8\pi F^2}{\pi a^2 F^2/4} \int_0^{\theta_1} \frac{E(\theta) \sin\theta d\theta}{(1 + \cos\theta)^2} \quad [18]$$

$$= \frac{32}{a^2} \int_0^{\theta_1} \frac{E(\theta) \sin\theta d\theta}{(1 + \cos\theta)^2} \quad [19]$$

The concentration  $c(\lambda)$  represents the concentration due to the chosen wavelength band. The total concentration  $c_t$  is obtained by summing the energies concentrated in each wavelength band, that is,  $c_t$  is given by

$$c_t = \sum c(\lambda)$$

where the summation is extended over all the wavelength bands in the spectrum of the sun.

#### PROCEDURE

Given  $f(x)$  and  $e$  for a given wavelength band, determine from the equation

$$S = \int_0^1 f(x) x dx \quad [6]$$

Next determine  $x_1$  and  $x_2$  from the equations,

$$x_1 = (1 + \cos \theta)/2 \quad [13]$$

and

$$x_2 = (1 + \cos \theta)(\cos \theta)/2 \quad [14]$$

Then determine  $E(\theta)$  from the formula,

$$E(\theta) = \frac{2e}{\pi S} \int_{x_1}^{x_2} f(x) \phi(x) x dx + \frac{e}{S} \int_0^{x_2} f(x) x dx \quad [15]$$

where

$$\phi(x) = \arcsin \left\{ \cot \theta \sqrt{\left( \frac{1 + \cos \theta}{x} \right)^2 - 1} \right\} \quad [12]$$

Then calculate

$$c(\lambda) = \frac{32}{a^2} \int_0^{\theta_1} \frac{E(\theta) \sin\theta d\theta}{(1 + \cos\theta)^2} \quad [19]$$

Finally calculate  $c_t$ , where  $c_t$  is given by

$$c_t = \sum c(\lambda)$$

#### CHECK OF THE FORMULAS FOR A UNIFORM SUN

The concentration factor for a uniform sun has been given by Bliss.<sup>1</sup> We will see if the formulas developed above give the same result.

For a uniform sun  $f(x) = 1$  and  $S = 1/2$ , so that we have

$$E(\theta) = \frac{e}{2\pi S} 4 \int_{x_1}^{x_2} \phi(x) x (-dx) + \frac{e}{S} \int_0^{x_2} x dx$$

$$= (e/\pi) (\pi x_1 x_2 - \pi x_2^2) + e x_2^2 = e x_1 x_2$$

$$= e (1 + \cos \theta)^2 (\cos \theta)/4$$

Substituting this value in Equation [17], there results

$$c = \frac{32e}{a^2} \int_0^{\theta_1} \sin\theta \cos\theta d\theta = \frac{8}{a^2} \frac{\sin^2 \theta_1}{2}$$

$$= (4e \sin^2 \theta_1)/a^2 = Ce$$

where  $C$  is the concentration factor of Bliss, which gives

$$C = (4 \sin^2 \theta_1)/a^2$$

This checks the result given by Bliss.

As a further check let us compare with the formula given by Jose<sup>2</sup> for the concentration factor.

According to Jose, this is given by

$$C = \frac{4}{a^2} \int_0^{\theta_1} R_x \sin\theta d\theta$$

where  $R_x$  is given by

$$R_x = \frac{E_\theta}{e} \frac{4}{(1 + \cos \theta)^2 \cos \theta} \sin 2\theta$$

so that

$$C = \frac{4}{a^2} \int_0^{\theta_1} \frac{E(\theta)}{e} \frac{4}{(1 + \cos \theta)^2} 2 \sin\theta d\theta$$

$$= \frac{32}{a^2} \int_0^{\theta_1} \frac{E(\theta)}{e} \frac{\sin\theta d\theta}{(1 + \cos \theta)^2}$$

This checks Equation [19] of this paper since  $C = c/e$ .



TABLE I

$x$	$\frac{f(x)}{\lambda}$							
	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
0.30	0.977	0.978	0.985	0.988	0.993	0.995	0.996	0.996
.50	.906	.937	.953	.967	.980	.980	.983	.988
.60	.855	.902	.928	.947	.969	.968	.972	.980
.70	.797	.855	.895	.922	.952	.953	.959	.969
.80	.710	.785	.847	.885	.928	.931	.939	.952
.90	.577	.687	.771	.821	.882	.891	.905	.928
.95	.470	.605	.703	.759	.837	.850	.870	.902
.975	.389	.537	.647	.710	.792	.814	.837	.875

TABLE II

$x$	$\frac{x f(x)}{\lambda}$							
	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
.30	.293	.293	.296	.296	.298	.299	.299	.299
.50	.453	.468	.477	.484	.490	.490	.492	.494
.60	.513	.541	.557	.568	.581	.581	.583	.588
.70	.558	.599	.627	.645	.666	.667	.671	.678
.80	.568	.628	.678	.708	.742	.745	.751	.761
.90	.519	.618	.694	.739	.794	.802	.814	.835
.95	.497	.575	.668	.721	.795	.807	.826	.855
.975	.379	.524	.631	.692	.772	.794	.816	.853

TABLE III  
PARTIAL INTEGRANDS FOR S

$x$	$\lambda$							
	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
0.00 - 0.30	0.0440	0.0440	0.0444	0.0444	0.0447	0.0449	0.0449	0.0449
.30 - .50	.0746	.0761	.0773	.0780	.0788	.0789	.0791	.0793
.50 - .60	.0483	.0505	.0527	.0526	.0536	.0536	.0538	.0541
.60 - .70	.0536	.0570	.0592	.0607	.0624	.0624	.0627	.0633
.70 - .80	.0563	.0614	.0653	.0677	.0704	.0706	.0711	.0720
.80 - .90	.0544	.0623	.0686	.0724	.0768	.0774	.0783	.0798
.90 - .95	.0242	.0299	.0341	.0365	.0397	.0402	.0410	.0423
.95 - .975	.0103	.0137	.0163	.0177	.0196	.0200	.0205	.0214
.975 - 1.00	.0047	.0065	.0079	.0087	.0097	.0099	.0102	.0107
	0.3704	0.4017	0.4258	0.4387	0.4557	0.4579	0.4616	0.4678

## CALCULATIONS

By interpolation from Table 814,<sup>3</sup> the values given in Table I were derived.

From the values given in Table I, the values of  $f(x)x$  were calculated and are given in Table II.

From the values given in Table II, the values of  $S = \int_0^1 f(x) x dx$  were calculated and are given in Table III.

The values of  $e$  given in Table IV were taken from the paper by Wight.<sup>4</sup> The value of the wavelength at the center of the band as well as the wavelength interval are also given in Table IV.

From the values for  $e$  given in Table IV and the values of  $S$  given in Table III, the constants  $2e/\pi S$  and  $e/S$  were calculated and are given in Table V.

TABLE IV

$\lambda$	$e$	$\lambda_e$	$\Delta\lambda$
0.35 - 0.50	0.44	0.425	0.15
.50 - .75	.48	.625	.25
.75 - 1.00	.28	.875	.25
1.00 - 1.50	.32	1.25	.50
1.50 - 2.00	.14	1.75	.50
2.00 - 2.50	.04	2.25	.50
2.50 - 3.00	.03	2.75	.50
3.00 - 4.50	.03	3.75	1.50

The values of  $x_1$  and  $x_2$  were calculated and the results are given in Table VI.

The values  $x_1 - x_2$  were split up into intervals and the value of  $\phi(x)$  calculated for the end points of each interval. The results are given in Table VII.

Corresponding to the same intervals, the values of  $f(x)$  were calculated by interpolation from Table I, and the results entered in Table VIII.

TABLE V

$\lambda$	$2e/\pi S$	$e/S$
0.425	0.756	1.188
0.625	.761	1.295
.875	.419	0.658
1.25	.464	.729
1.75	.195	.307
2.25	.0556	.0874
2.75	.0414	.0650
3.75	.0411	.0646

TABLE VI

$\theta$	$x_1$	$x_2$	$\Delta x = x_1 - x_2$
0°	1.000	1.000	0.000
10°	0.993	0.978	.015
20°	.970	.912	.058
30°	.933	.808	.125
40°	.883	.676	.207
50°	.822	.529	.293
60°	.750	.375	.375
70°	.671	.229	.442
80°	.587	.102	.485
90°	.500	.000	.500

TABLE VII

$\theta$	Intervals	$\Delta x$	$x$	$\phi(x)$
10°	1	0.015	0.978	1.571
			.993	0.000
20°	1	.058	.912	1.571
			.970	0.000
30°	1	.125	.808	1.571
			.933	0.000
40°	2	.103	.676	1.571
			.779	0.693
			.883	.000
50°	3	.098	.529	1.571
			.627	0.792
			.725	.466
			.822	.000
60°	4	.094	.375	1.571
			.469	0.793
			.563	.533
			.657	.323
			.750	.000
70°	4	.1105	.2290	1.571
			.3395	0.670
			.4500	.415
			.5605	.242
			.6710	.000

TABLE VIII

 $f(x)$   
 $\lambda$ 

$\theta$	$x$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
10°	0.978	0.342	0.531	0.569	0.625	0.697	0.716	0.718	0.770
20°	.912	.551	.667	.755	.806	.871	.881	.897	.922
30°	.808	.699	.777	.841	.880	.924	.928	.936	.950
40°	.676	.811	.866	.903	.928	.956	.957	.963	.972
	.779	.728	.800	.857	.893	.933	.936	.943	.956
50°	.529	.891	.927	.946	.961	.987	.977	.980	.986
	.627	.840	.890	.919	.940	.964	.964	.969	.977
	.725	.775	.837	.883	.913	.946	.948	.954	.965
60°	.375	.950	.962	.973	.980	.988	.989	.991	.993
	.469	.917	.943	.958	.970	.982	.982	.985	.989
	.563	.874	.915	.937	.954	.973	.972	.976	.985
	.657	.822	.875	.910	.933	.959	.959	.965	.974
70°	.2290	.982	.983	.989	.991	.995	.996	.997	.997
	.3395	.963	.970	.979	.984	.990	.992	.993	.994
	.4500	.924	.961	.961	.972	.983	.984	.986	.990
	.5605	.875	.916	.940	.955	.973	.973	.976	.984

TABLE IX

 $E_1(\theta)$   
 $\lambda$ 

$\theta$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
10°	0.00298	0.00466	0.00275	0.00334	0.00157	0.00046	0.00034	0.00037
20°	.0173	.0211	.0132	.0155	.00706	.00204	.00154	.00158
30°	.0419	.0469	.0280	.0324	.0143	.00409	.00307	.00311
40°	.0641	.0699	.0407	.0466	.0203	.0060	.00435	.00449
50°	.0777	.0828	.0471	.0534	.0231	.0066	.00491	.00493
60°	.0751	.0784	.0439	.0467	.0211	.0060	.00451	.00451
70°	.0575	.0589	.0328	.0366	.0155	.0044	.00330	.00329

TABLE X

 $E_2(\theta)$   
 $\lambda$ 

$\theta$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
10°	0.4353	0.5125	0.2757	0.3142	0.1373	0.0393	0.0294	0.0296
20°	.4004	.4643	.2472	.2803	.1216	.0347	.0260	.0261
30°	.3342	.3807	.2003	.2254	.0970	.0277	.0207	.0206
40°	.2468	.2770	.1443	.1612	.0689	.0196	.0147	.0146
50°	.1575	.1745	.0901	.1004	.0427	.0122	.0091	.0090
60°	.0854	.0939	.0482	.0537	.0229	.0065	.0049	.0048
70°	.0399	.0435	.0223	.0247	.0105	.0030	.0022	.0022

TABLE XI

	$E(\theta)$ $\lambda$							
	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
10°	0.4383	0.5172	0.2785	0.3175	0.1389	0.0398	0.0297	0.0300
20°	.4177	.4854	.2604	.2958	.1287	.0367	.0275	.0277
30°	.3761	.4276	.2283	.2578	.1113	.0318	.0238	.0237
40°	.3109	.3469	.1850	.2078	.0892	.0256	.0191	.0191
50°	.2352	.2573	.1372	.1538	.0658	.0188	.0140	.0139
60°	.1605	.1723	.0921	.1004	.0440	.0125	.0094	.0093
70°	.0974	.1024	.0551	.0613	.0260	.0074	.0055	.0055

From the values of the constants given in Table V, the values of  $\phi(x)$  given in Table VII, and the values of  $f(x)$  given in Table VIII, the integrals  $E_1(\theta)$  were calculated, and the results are given in Table IX. The intervals given in Table VII were used.

From the values of  $x_2$  given in Table VI and the values of  $f(x) \times dx$  given in Table III, the values of the integrals  $E_2(\theta)$  were calculated. The results are given in Table X.

The results entered in Tables IX and X were added to give  $E(\theta)$  and are entered in Table XI.

Next the values of the function  $\theta/(1 + \cos \theta)^2$  were calculated and entered in Table XII.

TABLE XII

$\theta^\circ$	$\sin \theta / (1 + \cos \theta)^2$
10.....	0.0442
20.....	.0909
30.....	.144
40.....	.206
50.....	.284
60.....	.385
70.....	.522

From the values of  $E(\theta)$  given in Table XI and the values of  $\sin \theta / (1 + \cos \theta)^2$  given in Table XII, the values of the elements

$$\frac{16}{0.0093} E(\theta) [(\sin \theta) / (1 + \cos \theta)^2 d\theta]$$

were calculated and entered in Table XIII.

TABLE XIII

	$\lambda$							
$\theta$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
10°	625	738	397	453	198	57	42	43
20°	1230	1420	764	868	378	108	81	81
30°	1750	1990	1060	1200	517	148	110	110
40°	2070	2310	1230	1380	593	170	127	127
50°	2160	2360	1260	1410	603	172	128	127
60°	1990	2140	1140	1250	547	155	117	116
70°	1640	1730	929	1030	438	125	93	93

By adding the values given in Table XIII, the values of  $c(\lambda)$  were obtained for various values of  $\lambda$  as given in Table XIV. The values were added to give the final values of the concentration for  $\theta = 50^\circ$ ,  $60^\circ$ , and  $70^\circ$ .

TABLE XIV

	$c(\lambda)$		
	$\theta = 50^\circ$	$\theta = 60^\circ$	$\theta = 70^\circ$
0.425	14,510	18,660	22,290
.625	15,276	19,776	23,646
.875	8,162	10,562	12,631
1.25	9,212	11,872	14,152
1.75	3,975	5,125	6,110
2.25	1,138	1,465	1,745
2.75	848	1,093	1,303
3.75	809	1,092	1,301
	53,970	69,645	83,178

The final results give the energy in calories per square centimeter per minute concentrated in the focal spot. The corresponding values in calories per square centimeter per second are given by

Concentration (cal/cm <sup>2</sup> /sec)	
50°.....	896
60°.....	1161
70°.....	1386

These values are on the basis of a total of 1.76 cal per sq cm per min received at the earth's surface.

Comparing with the values obtained by Jose<sup>2</sup> for a total of 1.94 cal per sq cm per min, we find:

	Simon	Jose	Ratio S/J
50°	53,970	55,300	0.976
60°	69,645	71,800	.970
70°	83,178	85,500	.973

Or, if we calculate the concentration ratio by dividing these values respectively by 1.76 and 1.94, we obtain

	Simon	Jose	Ratio S/J
50°	30,700	28,498	1.076
60°	39,600	37,016	1.069
70°	47,300	44,104	1.072

The difference is apparently due to the fact that Jose has used an average distribution curve for all the wavelengths, while in this report distribution curves corresponding to various wavelength bands have been used. While the concentration ratio obtained by Simon is 7.2 per cent higher than that of Jose, the total energy used by Simon is 9.3 per cent lower than that used by Jose, which accounts for the fact that Simon obtains an energy concentration 2.7 per cent lower than that of Jose. However, Simon calculates the concentration on the basis of the energy reaching the surface of the earth (Wight) while Jose calculates the concentration on the basis of the energy striking the outer atmosphere, i.e., he neglects atmospheric absorption.

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# THE LOSS OF ENERGY BY ABSORPTION AND REFLECTION IN THE HELIOSTAT AND PARABOLIC CONDENSER OF A SOLAR FURNACE\*

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This paper analyses the reflection and absorption losses for back-silvered plate glass mirrors such as would be used in a solar furnace. Taken into account are: the amount of incident light reflected from the surface of the glass plate, the amount absorbed by the known thickness of the glass plate, the amount lost on reflection from the silver surface, and the higher order terms showing the losses as the light is reflected and transmitted back and forth within the glass.

## THE METHOD

If we denote by  $r$  the fraction of the intensity of the incident light which is reflected from the front surface of a mirror, by  $s$  the fraction of the intensity of the incident light which is refracted by the glass, by  $\rho$  the fraction of the intensity of the light incident on the silver surface which is reflected therefrom, by  $r'$  the fraction of the

light incident internally on the glass surface reflected therefrom, by  $s'$  the fraction of the light incident internally on the glass surface refracted into the air, and by  $R$  the sum of the fractional intensities reflected by the combination, we see from Fig. 1 that

$$R = r + \rho s s' + r' \rho s \rho s' + r' \rho^2 s \rho s' + \dots \quad [1]$$

Now we have the relation  $s = (1 - r)$ , and it can easily be shown that  $r' = r$  and  $s' = s$ , so that we can put

$$R = r + \rho(1 - r)^2 [1 + r\rho + (r\rho)^2 + \dots] \quad [2]$$

If now we use the subscripts  $p$  and  $s$  to indicate the parallel and perpendicular components of the light, we have according to Fresnel

$$r_p = [\tan(\phi - X)/\tan(\phi + X)]^2 \quad [3]$$

and

$$r_s = [\sin(\phi - X)/\sin(\phi + X)]^2 \quad [4]$$

where  $\phi$  is the angle of incidence and  $X$  the angle of refraction; we additionally note that

$$\sin X = (\sin \phi)/N \quad [5]$$

where  $N$  is the index of refraction of the glass, from which the angle of refraction can be calculated provided that the angle of incidence is given.

For the quantities  $\rho_p$  and  $\rho_s$  we have the relations

$$\rho_p = \frac{(\eta - N/\cos \phi)^2 + K^2}{(\eta + N/\cos \phi)^2 + K^2} \quad [6]$$

and

$$\rho_s = \frac{(\eta - N/\cos \phi)^2 + K^2}{(\eta + N/\cos \phi)^2 + K^2} \quad [7]$$

where  $\eta$  is the index of refraction of the silver and  $K$  the extinction coefficient, and from these equations  $R_p$  and  $R_s$  can be calculated. Assuming the incident light unpolarized, the resultant  $R$  is given by

$$R = (R_p + R_s)/2 \quad [8]$$

## CALCULATION OF THE REFLECTIVITY OF A GLASS-SILVER MIRROR

Let  $I$  indicate the incident intensity of the light falling on the mirror,  $E$  the emergent intensity,  $\mu$  the absorption

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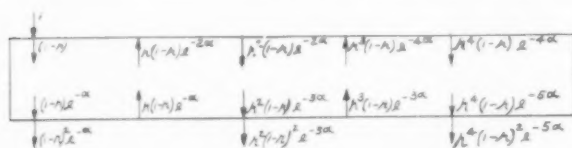
FIG. 1 — Reflection of light from a plate glass mirror.



FIG. 2 — Reflection of light from a plate glass mirror in terms of incident and emergent intensities.



FIG. 3 — Transmission of light by a sheet of plate glass.





coefficient of the glass, and  $t$  the thickness of the glass, then upon referring to Fig. 2 we have the following equations:

$$\begin{aligned} I &= I_0 s e^{-\mu t/\cos X} \\ I_1 &= \rho I e^{-\mu t/\cos X} \\ I_2 &= r' I_1 e^{-\mu t/\cos X} \\ I_3 &= \rho I_2 e^{-\mu t/\cos X} \\ I_4 &= r' I_3 e^{-\mu t/\cos X} \\ I_5 &= \rho I_4 e^{-\mu t/\cos X} \end{aligned} \quad [9]$$

and so on.

$$\begin{aligned} E &= r I_0 \\ E_1 &= s' I_1 \\ E_3 &= s' I_3 \\ E_5 &= s' I_5 \end{aligned} \quad [10]$$

and so on.

Substituting  $(1 - r)$  for  $s$  and  $s'$  and  $r$  for  $r'$ , we have as the sum of the emergent intensities

$$\begin{aligned} R &= \sum E/I_0 = r + (1 - r)^2 \rho e^{-2a} \\ &\quad + (1 - r)^2 r \rho^2 e^{-4a} + (1 - r)^2 r^2 \rho^3 e^{-6a} + \dots \\ &= r + (1 - r)^2 \rho [\epsilon^{-2a} + r \rho \epsilon^{-4a} + r^2 \rho^2 \epsilon^{-6a} + \dots] \end{aligned} \quad [11]$$

where we have put

$$\epsilon^{-2a} = e^{-2\mu t/\cos X} \quad [12]$$

If we let  $f = \epsilon^{-a}$  we can further write that

$$R = r + (1 - r)^2 f^2 \rho [1 + r \rho f^2 + r^2 \rho^2 f^4 + \dots] \quad [13]$$

The quantities  $r$ ,  $\rho$  and  $f$  are functions of the angle of incidence as well as of the wavelength.

It remains to show how  $f_0$ , the fractional part of the light incident on a plate of glass which is absorbed by a known thickness  $t_0$  of the glass, can be determined from the measured fraction  $p$  of the light transmitted by the glass. This transmitted portion  $p$  is given by

$$\begin{aligned} p &= (1 - r)^2 \epsilon^{-a_0} + r^2 (1 - r)^2 \epsilon^{-3a_0} \\ &\quad + r^4 (1 - r^2) \epsilon^{-5a_0} + \dots \end{aligned} \quad [14]$$

Since  $r$  is approximately 4 per cent, we can write to a close degree of approximation

$$p = (1 - r)^2 \epsilon^{-a_0} = (1 - r)^2 f_0 \quad [15]$$

whence

$$f_0 = p/(1 - r)^2 \quad [16]$$

In order to calculate  $f$  we note

$$f = \epsilon^{-\mu t}, f_0 = \epsilon^{-\mu t_0}, t = t_0/\cos X$$

whence we have

$$\log_{10} f = (\log_{10} f_0)/\cos X \quad [17]$$

## CALCULATIONS

In a previous report<sup>1</sup> we have calculated the energies contained in various wavelength bands in the spectrum of the sun. We shall use the same bands in this report. In Table I the quantities  $\eta$ ,  $K$ ,  $N$ , and  $K^2$  are given for the glass and the silver coating. The index of refraction of water-white plate glass as a function of wavelength was not available; however, the Pittsburgh Plate Glass Company has advised it would be approximately the same as for crown-silicate glass. The values for this glass are given by Morey.<sup>2</sup> The values of  $\eta$  and  $K$  were extrapolated from the data given in the Smithsonian Tables.<sup>3</sup>

TABLE I

$\lambda$	$\eta$	$K$	$K^2$	$N$
0.425	0.16	2.20	4.84	1.537
.625	.17	4.05	16.41	1.522
.875	.205	6.06	36.73	1.514
1.25	.345	8.83	77.99	1.510
1.75	.557	12.3	151.3	1.505
2.25	.77	15.4	237.2	1.498
2.75	1.36	18.5	342.3	1.490
3.75	2.93	26.3	691.9	1.450

From Equations [3], [4], [5], and [8], the values of  $r$  corresponding to various angles of incidence and wavelengths were calculated and are given in Table II.

Next, from Equations [6], [7], and [8], the values of

TABLE II  
 $\lambda$

$\phi$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
0°	0.0438	0.0429	0.0418	0.0413	0.0406	0.0397	0.0396	0.0337
5°	.0440	.0428	.0420	.0408	.0408	.0400	.0392	.0336
10°	.0446	.0426	.0414	.0410	.0404	.0395	.0387	.0337
15°	.0448	.0425	.0419	.0411	.0405	.0395	.0386	.0339
20°	.0449	.0431	.0422	.0414	.0406	.0400	.0389	.0340
25°	.0455	.0434	.0421	.0419	.0415	.0401	.0395	.0342
30°	.0464	.0445	.0434	.0427	.0423	.0412	.0406	.0356
35°	.0478	.0458	.0448	.0443	.0436	.0427	.0417	.0366
40°	.0500	.0487	.0477	.0469	.0463	.0444	.0443	.0392

TABLE III  
 $\lambda$

$\phi$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
0°	0.873	0.946	0.969	0.975	0.978	0.981	0.977	0.980
5°	.873	.946	.968	.974	.979	.981	.977	.978
10°	.873	.946	.969	.973	.979	.981	.977	.977
15°	.873	.947	.968	.974	.979	.981	.978	.977
20°	.873	.947	.968	.974	.978	.981	.978	.977
25°	.873	.946	.968	.974	.979	.981	.977	.977
30°	.873	.947	.968	.974	.978	.981	.977	.975
35°	.874	.947	.968	.974	.978	.981	.977	.975
40°	.875	.946	.967	.973	.978	.980	.978	.976

$\rho$  were calculated for various angles and wavelength bands and are given in Table III.

From a table given by Wight<sup>4</sup> for the transmission of water-white plate glass, the factors  $t_0$  were calculated. The data were extrapolated beyond 2.10  $\mu$  and are given in Table IV.

TABLE IV

$\lambda$	$f_0$
0.425.....	0.991
.625.....	.997
.875.....	.991
1.250.....	.980
1.750.....	.927
2.250.....	.912
2.750.....	.911
3.750.....	.901

From the values given in Table IV, the values of  $f$  were calculated for various angles according to Equation [17]. The results are given in Table V.

From the values of  $r$ ,  $\rho$ , and  $f$  given in the tables, the values of  $R$  for an angle of incidence of 40°, corresponding to an angle of elevation of the sun of 80°, and for the energy in the various bands as given in a previous report,<sup>1</sup> the energy reflected from the heliostat was calculated, and the results are given in Table VI.

TABLE VI  
THE HELIOSTAT  
Angle of elevation of the sun = 80°  
(cal/cm<sup>2</sup>/min)

$\lambda$	$R$	$e$	$Re$
0.425	0.857	0.44	0.377
.625	.939	.48	.451
.875	.948	.28	.265
1.250	.929	.32	.297
1.750	.827	.14	.116
2.250	.756	.04	.030
2.750	.752	.03	.023
3.750	.735	.03	.022
Sum		1.76	1.58

One notes that the energy reflected by the heliostat is 89.8 per cent of the energy falling on it when the angle of elevation of the sun is 80°.

Next the values of  $R$  corresponding to various wavelengths and angles  $\phi$  were calculated. The results are given in Table VII. Only the first two terms of Equation [13] were used.

Taking the values of  $E(\theta)$  given in a previous report<sup>1</sup> for various angles  $\theta$  and multiplying these values by the corresponding values of  $\phi = \theta/2$  and integrating the energies corresponding to various wavelengths and angles  $\theta$  of 50°, 60°, and 70°, the partial fluxes were calculated and are given in Table VIII for an angle of elevation of the sun of 80°.

TABLE VIII  
(cal/cm<sup>2</sup>/min)

$\lambda$	50°	60°	70°
0.425	10,592	13,642	16,302
.625	13,482	17,452	20,872
.875	7,350	9,510	11,427
1.25	7,990	10,290	12,260
1.75	2,761	3,558	4,319
2.25	699	900	1,072
2.75	516	665	792
3.75	494	636	751
Sum	43,884	56,653	67,801

On the basis of  $R = 1$ , i.e., unit reflectivity, we obtained the following values for the energy, in cal per sq cm per min,<sup>1</sup>

50°	60°	70°
53,970	69,645	83,178

giving for the combined reflectivities of the heliostat and paraboloid,

50°	60°	70°
81.3%	81.3%	81.5%

TABLE V  
 $\lambda$

$\phi^\circ$	0.425	0.625	0.875	1.25	1.75	2.25	2.75	3.75
0	0.991	0.997	0.991	0.980	0.927	0.912	0.911	0.901
5	.991	.997	.991	.980	.927	.912	.911	.901
10	.991	.997	.991	.980	.927	.911	.910	.901
15	.991	.997	.991	.980	.926	.911	.910	.901
20	.991	.997	.991	.980	.925	.910	.909	.898
25	.991	.997	.991	.979	.924	.908	.907	.897
30	.991	.997	.991	.979	.923	.907	.906	.895
35	.990	.997	.991	.978	.921	.905	.904	.893
40	.990	.997	.991	.978	.920	.903	.902	.890

TABLE VII  
 $\phi$

$\lambda$	5°	10°	15°	20°	25°	30°	35°	40°
0.425	0.854	0.857	0.857	0.857	0.857	0.858	0.856	0.857
.625	.939	.939	.940	.940	.939	.940	.939	.939
.875	.950	.949	.950	.949	.950	.949	.950	.948
1.25	.934	.933	.932	.934	.932	.933	.930	.929
1.75	.841	.841	.840	.837	.837	.833	.830	.827
2.25	.817	.815	.815	.813	.809	.806	.804	.756
2.75	.812	.809	.810	.808	.805	.805	.799	.752
3.75	.795	.794	.794	.789	.787	.783	.780	.735



while we note for the heliostat alone the reflectivities

50°	60°	70°
89.8%	89.8%	89.8%

leaving as the reflectivities of the paraboloid

50°	60°	70°
90.5%	90.5%	90.8%

On the basis of 1.76 cal per sq cm per min incident solar radiation, these would correspond to energy concentrations in cal per sq cm per sec of

50°	60°	70°
731	944	1130

#### REFERENCES

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2. George W. Morey, *Properties of glass*. 2nd ed. N.Y., Reinhold, 1954.
3. William E. Forsythe, *Smithsonian physical tables*, 9th rev. ed. Wash., Smithsonian Institution, 1954. p. 559.
4. Ralph H. Wight. *J. Solar Energy Sci. Eng.* 1(2-3):84, 1957.

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## WORLD RESEARCH ACTIVITIES

The following survey of world-wide solar energy research activities is intended to form a continuing current supplement to the directory section in *Applied Solar Energy Research* (Stanford Research Institute, 1955). As this section will appear at irregular intervals in succeeding issues, the editor will welcome any information on activities not mentioned below or in earlier issues, and on future developments in the utilization of solar energy.

### AUSTRALIA

Commonwealth Scientific and Industrial Research Organization, Engineering Section. P.O. Box 26, Highett, S.21, Victoria.  
R. N. Morse.

Continued development work on solar water heaters and investigated a number of aspects of their performance. These investigations have been mainly into problems associated with their design, manufacture, and installation, including protection from frost, effect of orientation, and over-all efficiency of collection. Also working on the preparation of selective surfaces for the absorption of solar radiation and the development of a radiation-sensitive relay for forced-circulation water heaters.

Commonwealth Scientific and Industrial Research Organization, Division of Industrial Chemistry.  
P.O. Box 4331, G.P.O., Melbourne, Victoria.  
B. W. Wilson.

Designed and constructed solar energy absorbers for heating air and drying vine fruit, which were tested under field conditions.

New South Wales University of Technology, School of Mechanical Engineering. Broadway, Sydney, N.S.W.

A. H. Willis; C. M. Sapsford.

Study commenced on design and operating characteristics of thermosyphon-operated solar water heaters for domestic use. Further work contemplated on discrepancies noted in application of published heat loss expressions for collector surface. Observations made on transmissivity of locally available glass. Observations of solar radiation using Kipp Solarimeters commenced June, 1957, total and diffuse radiation being observed continuously at Kensington and Sydney, also total radiation at Broken Hill, N.S.W. Estimations of solar radiation for Australian conditions prepared using records of sunshine hours from

Weather Bureau, and curves prepared to summarize effect, on solar energy received, of variations in angles of tilt and bearing for a flat-plate solar collector.

### BELGIAN CONGO

Institut pour la Recherche Scientifique en Afrique Centrale. Lwiro (Katana), Bukavu.  
G. Bonnet.

Operated solar radiation laboratory since 1952, with thermoelectric receivers (Moll and Volochine), electronic potentiometric recorders, and 3 silver-disk pyrheliometers as reference. Recordings made of the direct, total, and diffuse radiation, the duration of insolation, the total ultraviolet radiation (cadmium cell), the energy in various spectral ranges (colored filters) for total and direct radiation, the degree of refrigeration (Davos frigori-meter), the energetic balance of radiation (Beckman & Whitley), and the total and direct light.

J. Cl. De Bremaecker.

Operating two prototypes of solar water heaters especially adapted to underdeveloped countries. More heaters will be built. Economic studies of their use have been made for most of the Congo. Simple solar cookers with a mirror adjustment which does not move the focal point built and tested in native cities. Small solar furnace to be built in near future.

S. J. L. Guislain.

Registered total solar radiation on a horizontal plane at different places in Belgian Congo and Ruanda-Urundi Territories. In connection with tropical housing research, studied: (1) basic research on periodic heat transmission in buildings; (2) sol-air temperature in relation to screening effects of overhang on neighbouring buildings; (3) influence of solar heat on inner room climate; (4) experimental model of an electric analog for predicting thermal behaviour and performances of buildings under different outdoor climatic conditions including ventilation; (5) measurements of the efficiency of various methods and devices tending to improve natural conditioning (sun protection).

### BURMA

Union of Burma Applied Research Institute. Junction of Kaba Aye Pagoda-Kanbe Roads, Rangoon.

Freddy Ba Hli; U Maung Maung; U Thoun.

Active projects in the utilization of solar energy for: (1) salt production using both solar cookers and large shallow black rubber evaporating basins, in order to reduce the cost and improve the quality of salt; (2) various

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methods of domestic water heating; (3) domestic and industrial refrigeration. The Institute's solar cookers are being used in the production of beverages from palm juice and other products and have been demonstrated in various parts of Burma where wood fuel is scarce and where they can be built locally at a cost of about \$7-\$12.

## CHILE

Instituto Nacional de Investigaciones Tecnológicas y Normalización. Universidad Católica, Santiago.  
Mario Galdames.

Constructed and studied 2 x 3.5 x 7 m water heater consisting of two layers of glass over a copper-lined box and copper coil, and two tanks, a regulator of 500 liters capacity and an accumulator of 200 liters. Temperatures recorded during the summer months. Future investigations will be of the over-all efficiency of the installation and of the most adequate quality of glass.

## EGYPT

University of Cairo, Electrical Engineering Dept.  
Giza.

M. S. M. Abou-Hussein.

Constructed a high temperature furnace using a 3.2-ft diameter silver-coated glass reflector which attains a focal temperature of about 2000°C. Constructed flat-plate collectors using from 1-2 glass plates 1/8-in. thick, for water and space heating, drying, baking, steam generation, distillation, water pumping, and other applications. Solar power stations using both parabolic and flat mirrors under construction. Studying heat-transfer, surface-selectivity, and light storage problems.

## ENGLAND

Woolwich Polytechnic. London, S.E. 18.

Harold Heywood.

During summer of 1957, visited Malta to advise on the possibilities for solar energy developments. Program of research in the fields of water heating and distillation formulated, and trial equipment now under construction for preliminary tests.

J. C. V. Chinnappa.

Studying the fundamental properties of the ammonia-water absorption cycle for refrigeration.

G. Hassan.

Conducting research on the factors affecting the water circulation in flat-plate solar water heaters.

## FRENCH WEST AFRICA

Université de Dakar, Laboratoire Physique Météorologique. B.P. 6,049, Dakar-Etoile.

H. Masson; Mlle de Pouques; Mlle Salvador; M. Petit.

Experimental research includes: (1) distillation; (2) heating of water by plane insulator and cylindro-parabolic insulator with automatic orientation; (3) sea-weed culture (Cyanophyce); (4) production of motive power using the SOMOR-type pump; (5) production of cold.

## GERMANY

J. H. Dannies, engineer. Goebenstrasse 31, Bonn.

Since 1935 carried out investigations on solar air-conditioning and refrigeration. Developed a system in which all intermediary machinery between solar radiation and saturated absorbent is omitted, so that the air conditioning can work without electric or other power. A refrigerator which uses dehumidified air for cooling developed; another model obtains temperature of 60 to 67.5°F with equipment utilizing 2 ventilators and a few heat exchangers. Solar resorption refrigeration plants developed which provide temperatures in the range 37.5°-40°F. Two types of solar water pumps developed to dehumidify air in connection with solar refrigerators: (1) serviceless water pumps, delivering drinking water from the air without any service, maintenance, etc.; (2) solar water pumps requiring opening of a cover above the absorbent in the evening.

Kohlenstoffbiologische Forschungsstation e.V. Essen.  
Herwarthstrasse 60, Essen-Bredeney.

Fritz Gummert; Marie Elisabeth Meffert; Hans-Martin Müller.

Continued work on the mass culture of single-celled green algae, particularly with the culture of *Scenedesmus obliquus* under favorable conditions.

Köln Universität, Institut für Gärungswissenschaft und Enzymchemie. An der Bottmühle 2, Köln.

Hermann Fink.

Experiments on dry unicellular green algae (*Scenedesmus obliquus*) indicate that the biological quality of algal protein is at least equal to that of milk protein and egg-white protein and has a decided liver-protecting effect. Following proposals from this group, experiments carried out in a clinic in Alexandria, where algae-feeding proved favorable for children suffering from Marasmus. These will be continued in a Libyan hospital.

## ISRAEL

Hebrew University, Dept. of Botany. Jerusalem.

A. M. Mayer.

Completed work on the mass culture of *Chlorella*, under the auspices of the Ford Foundation.

Israel Institute of Technology, Solar Physics Laboratory. P.O. Box 4910, Haifa.

N. Robinson.

Studied various kinds of solar radiation and its application for hot water supply, water distillation, drying of agricultural products, and housing and health problems. The laboratory is now concentrating on solar physics studies.

Israel Institute of Technology, Division of Industrial Technology. P.O. Box 4910, Haifa.

K. D. Ofer.

Developed solar refrigerator which is now in pilot-plant stage. A full-scale model is being built.

National Physical Laboratory. P.O. B. 5192, Jerusalem.  
H. Tabor.

Work on methods producing selective black surfaces over large areas at low cost. Other applied research includes: (1) study of heat flow to increase collector efficiency; (2) design and testing of flat-plate collectors; (3) study of turbine designed for use with small solar engines of 1-10 hp; (4) heat storage systems; (5) use of absorption-type coolers operated by hot water or steam from solar collector, and consideration of solar cooling system of Dr. Altenkirch.

Sun Heaters Limited. 325 Hayarkon St., Tel-Aviv.  
R. Soborka.

Developing and selling commercially roof-mounted domestic solar water heaters. Standard models are of 120, 160, or 200 liters capacity, with 1, 2, or 3 collectors of either 1.5 sq m or 2 sq m area.

## ITALY

Universita degli Studi di Bologna, Istituto di Merceologia. Piazza Scaravilli 2, Bologna.

Constructing small vertical solar still with a useful surface of about 10 sq ft, to study the reduction of heat losses through the bottom of the salt-water tray.

Gaetano Vinaccia, architect. Via Claudio Monteverdi 20, Rome.

Studied solar energy availability in Caracas, Venezuela, and compared cost of solar energy with that of local electricity and petroleum. Developed a spherical solar absorber with a diameter of 11.30 m and a potential of 500,000 cal daily, for heating petroleum, and a 2-m spherical solar absorber with a heating capacity of 10,000 cal, for domestic water heating. Another absorber designed for the roof of a building, with an area of 300 sq m and a heating capacity of 1,650,000 cal.

## JAPAN

Government Industrial Research Institute, Solar Research Laboratory. Hirate-machi, Kita-ku, Nagoya.

Hisao Mii; Choji Noguchi; Nobuhei Hukuo; Tetsuo Noguchi; Shozo Iida; Ikuya Fujishiro; Masao Mizuno; Takeshi Kozuka; Masaie Yoshida.

150-cm diameter solar furnace constructed in May, 1958, consisting of a 240-ft sq heliostat of 16 glass mirrors with aluminum front surface protected by a thin layer of silicon monoxide, a back-silvered glass searchlight mirror of 150 cm diameter, and an electronic-hydraulic tracking system. Calculated value of the flux density of the solar radiation at the focal point, 2500 watts per sq cm.

## LEBANON

Adnan Tarcici. c/o Yemen Legation, Alhamra St., Beirut.

Improved collapsible solar cooker design and intends to sell it commercially. Developed 3 light-weight models which are now being produced in France at the rate of about 30 units a day.

## SOUTH AFRICA

South African Council for Scientific and Industrial Research, National Mechanical Engineering Research Institute. P.O. Box 395, Pretoria.

A. Whillier.

Investigating cheaper methods of solar water heater construction. Several heaters installed in private homes to obtain statistical information on the performance. Two thermosyphon and one forced-circulation models now being tested.

Three-bedroom house completed at Krugersdorp (elevation 5800 ft) in September 1957, using floor perimeter forced-air heating system with solar energy and electric auxiliary power. Winter trials will be made in June, July, and August of 1958. The solar collector of 40 sq ft performed satisfactorily during the summer, has been increased to 80 sq ft for this winter, and will ultimately be 150 sq ft. Air system is designed for summer cooling using night-time cool air with crushed rock regenerative storage.

As part of investigation of cheap fabrication methods for distillation units for rural drinking water supply, several still designs subjected to weathering and corrosion tests. Heat transfer in stills studied in an attempt to locate and eliminate the main causes of inefficiency.

Research furnace for studying high-temperature equilibria of various ceramics and for development of high-temperature thermocouple elements made from a surplus searchlight. Program set up to analyze all solar radiation data for the African continent, to be filed on punched cards. Further work undertaken in storage of heat in chemicals. A chemical heat storage system expected to perform close to the ideal will be set up and tested.

S. J. P. Joubert.

Research for private salt company has evolved an economical and efficient method of separating common salt and Glauber's salt from natural brines, using solar energy and night-time cooling.

## SWITZERLAND

Patek Philippe. Grand-Quai 22, Geneva.

G. Delessert; A. Krassölevitch; R. Brunner; A. Zibach.

Improved and developed commercial model of light-powered clock. Developed low-energy, high-sensitivity and high-precision small d-c and a-c motors especially suited to solar energy operation. Developed light-powered, miniature, transistorized frequency and time standards of high accuracy.

## UNITED STATES

American Machine & Foundry Company, Central Research Laboratory. 200 Henry Street, Stamford, Conn.

L. H. Shaffer.

Work on the thermal, electrical, and mechanical phenomena connected with the utilization of solar energy.

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**American Society of Heating and Air-Conditioning Engineers, Research Laboratory.** 7218 Euclid Ave., Cleveland 3, Ohio.

C. M. Humphreys; L. F. Schutrum; Necati Ozisik.

Studied effectiveness of different shading devices in reducing solar heat gain through windows, with work completed on both canvas and metal awnings. Continuing research on the effectiveness of roller blinds initiated during the latter part of 1957. Sponsoring cooperative research at the University of Minnesota on the design of solar collectors.

**Arizona State College.** Tempe, Ariz.

Clement J. Kevane.

Developed methods for measurement of thermal properties such as thermal diffusivities, specific heat, and total emissivity in the College's 60-in. solar furnace.

Edward Y. Harper.

Directing class of senior mechanical engineers in a project experiment on the SOMOR solar pump. The pump is being readied for a performance test which will be run this summer.

**Arizona State College, Rocky Mountain Forest and Range Experiment Station.** Tempe, Ariz.

John P. Decker.

Developed rapid recording apparatus that incorporates an infrared gas analyzer as a precision hygrometer for measuring transpiration. Studies will be made of relationship between solar radiation and transpiration of desert vegetation. In the photosynthesis laboratory, studies were completed of time-course of  $\text{CO}_2$  exchange during alternating light and darkness, effect of light intensity on photorespiration, and effect of temperature on photorespiration.

**Arizona, University, Institute of Atmospheric Physics.** Tucson 25, Ariz.

A. R. Kassander; Raymond W. Bliss, Jr.; Earl Murry.

In process of consolidating all solar energy and radiation research activities into the Solar Energy Research Center, a small office-laboratory building equipped with a full-scale experimental heating-cooling system using solar energy for winter heating and "nocturnal" radiation for summer cooling. Initial work in solar energy utilization will consist of detailed performance studies of the experimental system, but it is anticipated that the work will soon be broadened to include a variety of research in thermal-process utilization of solar energy.

Now engaged in the following projects: (1) assembling and constructing equipment and instrumentation for the Solar Energy Research Center; (2) using spectrographic equipment and allied instrumentation in connection with the continuous measurement of atmospheric water content by the method of simultaneous comparisons of the intensity of the solar spectrum in regions affected and unaffected by water vapor absorption; (3) started research program to develop instruments of improved accuracy for the measurement of atmospheric radiation and net radiation exchange between ground and

sky; (4) continuing routine measurements of total solar intensity upon a surface normal to the sun's rays.

**Arizona, University, Dept. of Mechanical Engineering.** Tucson 25, Ariz.

A. R. Yappel; Richard Berg.

Completed first phase of tests on C. G. Abbot's solar boiler, and now studying methods of constructing a more accurate solar mirror, with a backing that will retain its true shape indefinitely. Further tests will be run to determine the output of the boiler and also to increase the efficiency.

**Curtiss D. Bassett, consulting engineer.** 201 East Liberty St., Ann Arbor, Mich.

Built and tested two amorphous cadmium sulfide solar generators; one of 1 sq ft flat-plate area which developed 0.75 v closed circuit emf is now being rebuilt to obtain greater power output.

**Battelle Memorial Institute.** 505 King Ave., Columbus 1, Ohio.

James A. Eibling.

Carrying out field evaluation of solar distillation units near Daytona Beach, Fla., for the Office of Saline Water. Studying and evaluating methods of heat storage for heat pumps, for the Edison Electric Institute.

**California, University, Agricultural Experiment Station.** Davis, Calif.

L. W. Neubauer; R. D. Cramer.

Studied heating and cooling of small homes exposed to strong, direct solar radiation and methods for the economical alleviation of heat problems.

C. F. Kelly and T. E. Bond.

Studied control of overheating by solar radiation in animal shelters and sheds. Stress is placed on several methods of keeping livestock cool, by shades, colors, evaporation, and air velocity.

**California, University, Algae Research Laboratory.**

1301 South 46th St., Richmond 4, Calif.

Clarence G. Golueke; William J. Oswald.

Continuing experiments on the use of continuous algal cultures to convert the elements in sewage and other organic wastes into animal feed, pure water, oxygen, and fuel. An experimental 2-acre pond operated at the Municipal Sewage Treatment Plant of the City of Concord, Calif., for a period of two years. Studies made of growth of algae on domestic sewage and separation of algae by alum coagulation and with an industrial centrifuge; and on recovering waste water through use of algal cultures. Experiments concluded which demonstrate on a laboratory scale a technically feasible industrial process which leads to storage of solar energy at output efficiencies of one or more per cent. New studies underway on the application of algae grown on sewage to the control of atmospheric composition in isolated environments.



**Clevett Engineering Laboratory.** 34 Harwood Road, Natick, Mass.  
M. Clevett.

Engaged in pilot production of two solar stove designs developed in this laboratory. A cardboard-plastic film cooker, an all-metal cook stove, and the same model in fiberglass with vacuum-plated mirror surface under construction. Stove will be sold commercially in three price ranges. Continued work on mobile solar furnaces for industrial use, using surplus radar reflectors. A 10-ft all-metal mobile solar furnace completed which will be used to power a hot-air engine. Developing a simple, low-cost domestic solar-heated hot water system which will be marketed as a complete packaged unit. Geodesic greenhouse also under development.

**Desert Sunshine Exposure Tests.** 7740 Ramona Road, Phoenix, Ariz.  
C. R. Caryl.

Completed a one-year study of the percent of ultraviolet radiation in Phoenix; since Nov. 1956, measured the daily amounts of solar radiation, in langley, on an equatorial mount, and recently began the measurement of of langley on an equatorial mount with ten mirrors attached. Made a study of the amount of fading of the textile association's Blue Standards during each of the 12 months of 1957.

**E. I. DuPont de Nemours & Company, Engineering Dept.** Wilmington 98, Del.  
F. E. Edlin.

Interested in making evaluations in the following fields: (1) 60-in. solar furnace for high temperature investigations; (2) inflated plastic solar stills for saline water distillation; (3) absorption collectors for space heating and cooling.

**Florida, University, Dept. of Mechanical Engineering.** Gainesville, Fla.

Erich A. Farber.

Solar radiation data, taken continuously 24 hours a day for the U.S. Weather Bureau, forms the basis for correlation of solar energy work and for correlation of weather conditions and solar energy availability. Studied artificial and solar radiation as it affects the surfaces of different materials reflecting and absorbing this energy. Studied different glasses, plastic films, etc., singly and in multiple layers and various combinations, in connection with the selective transmission characteristics for solar energy collectors.

Investigating new designs of solar water heaters incorporating more efficient and cheaper solar energy collectors and applying dual circulation designs which can be used in climates where freezing would damage conventional designs. Constructed and tested solar air heaters for house heating. Designed and tested high temperature, stationary solar absorber which is inexpensive and can produce temperatures on clear days much greater than with flat-plate collectors.

Built a 6 x 8 ft rotating parabolocylindrical reflector and investigated its performance. It is being used to drive

a small steam engine for power generation and efficiency studies and also to operate a standard absorption refrigeration system with ammonia and water, using cotton seed oil as the heated fluid. Built a hot-air engine operated by concentrating panels directing and superimposing the solar energy, and a small solar pump for irrigation work. Refrigerants other than ammonia and water being investigated.

Constructed a 60-in. searchlight, for use in high temperature work. Constructed scale working models of sewage digesters and tested them for possible application to solar energy heating of swimming pools. Preliminary work on solar distillation, cooking, and baking.

**Fordham University, High Temperature Laboratory.** New York City.

Tibor S. Laszlo (present address: Curtiss-Wright Corporation, Wood-Ridge, N.J.)

Measured the flux distribution as a function of the three spatial coordinates in the focal zone of a 60-in. solar furnace. The resolution of the radiometer was 0.116 in. Developed method to calculate blackbody temperature from brightness temperature measured in the solar furnace. The method can be used to determine emissivities at high temperatures. Improved electronic guiding mechanism.

**Hoffman Electronics Corporation.** 3761 South Hill St., Los Angeles 7, Calif.

B. L. Birchard; Norman J. Regnier; Lawrence W. Schmidt; Guy V. Wood (U.S. Forest Service).

Used silicon solar energy converters to power an automatic repeater radio station for the U.S. Forest Service, at Santiago Peak in Southern California. The circuits were completely instrumented in order to determine variations in numerous parameters involved, and tests were run for approximately 4 months. Another converter installed at the Los Angeles harbor lighthouse and evaluated as a navigational aid, in cooperation with the U.S. Coast Guard. Also developed silicon solar cell clock and water pump. Marketed Hoffman Solaradio. Developed silicon solar converters with contacts of aluminum rather than solder, specifically for use in space vehicles.

**Jet-Heet, Inc.** 152 South Van Brunt St., Englewood, N.J.

Manufactured solar ovens, 33 x 32 x 28 in., from designs of Maria Telkes, which are capable of reaching internal temperatures of 400°F. Manufactured solar stills, also based on Telkes' design, 3 x 8 ft x 4 in., capable of distilling up to 5 gal per day of pure water from saline or contaminated water.

John J. Dieckmann.

Manufactured flat-plate solar collectors, 4 x 10 ft x 6 in. deep, utilizing water as heat-collecting medium in Revere copper tube-in-strip. Both glass and plastic-covered models extensively tested during the summer of 1957 under conditions of forced and thermal circulation. Such collectors had a heat output of up to 7000 Btu per hour. Testing also conducted on a new method of inexpensively attaching aluminum header tubes to aluminum tube-in-strip.

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Charles W. Perry; John J. Dieckmann.

Developed solar-powered deep well pump designed to pump up to 5 gal per min from wells 100 ft or more in depth. Pump tested for operation with Jet-Heet solar collectors and pumped water from a simulated well installation. Design is based on patented principles of the Jet-Heet thermopump.

Hyman Appleton.

Tested and continued development of heat storage chemical salts. Work on select heat storage salts marketed by Jet-Heet under trade name "Transit-Heet" for use in temperature stabilization of shipping containers extended to several new low-cost heat-of-fusion materials with temperature ranges from 40° to 240°F which could be used in heat storage for home heating and cooling. Many Jet-Heet salts now being used in commercial applications for temperature stabilization of sensitive instruments drugs, vaccines, and perishable foods.

**Massachusetts Institute of Technology, Solar Energy Conversion Project, Space Heating Committee.**  
Cambridge 39, Mass.

Lawrence B. Anderson, *chairman of committee.*

Completed fourth in a series of MIT solar-heated houses, at Lexington, Mass. The heating system is designed to furnish most of the space heating and hot water heating requirements for a northern climate; it consists of a 640 sq ft, water-circulating collector which forms the south roof and wall of the house and a 1500-gal water storage tank, combined with a hot-air heating system. MIT engineers will retain separate access to a basement equipment and instrument room and will gather data on the system.

**Minneapolis-Honeywell Regulator Company, Research Center.** 500 Washington Ave. South, Hopkins, Minn.

Lorne Nelson; John E. Janssen.

Studied use and efficiency of a concentrating mirror in the collection of solar energy, using a 5-ft searchlight mirror which produced temperatures of 100° to 170°F. Supplied G.O.G. Löf of Denver, Colo., with a control system for his solar-heated home, in which air is used as the collecting media and a gravel bed for storage. To indicate the availability of solar energy a small analog of the solar collector was built. The temperature of a resistance element mounted in a black-covered box within the collector analog was used to indicate the level of available solar energy. An analysis of this control circuit, together with the overall operating performance of the solar heating system, will be made in the future.

Constructing control system for the solar heating and cooling system in the Solar Energy Research Station at the University of Arizona, in cooperation with R. W. Bliss, to provide for maximum utilization of the solar collector at the highest efficiency. Co-operated with MIT on control system for their Lexington solar house. A special control panel was constructed to facilitate the installation problem, with all control components wired directly to the

control panel. A critical analysis of this system will be made after some operational data have been gathered.

Last summer converted a surplus searchlight into a solar furnace. A tracking system was devised using 2 standard Honeywell Modutrol motors, two standard Brown amplifiers, and a special sensing device consisting of a lens and a target with 4 thermocouples fastened to it. Prepared a design for a calorimeter to be used as a primary standard for the large solar furnace at Cloudcroft, N.M. Specifications called for a waterflow calorimeter capable of measuring a radiation heat flow of 375 kw with a maximum error of  $\pm 1$  per cent.

**Minnesota, University, Dept. of Mechanical Engineering.** Minneapolis 14, Minn.

R. C. Jordan; J. L. Threlkeld.

Continuing program on investigation of fundamental characteristics of flat-plate collectors under controlled conditions. These studies include consideration of heat transfer from collector plate to collector fluid, configuration studies, albedo effects, and similar factors. Program under investigation on solar availability. Studying potential utilization of solar energy in heating buildings and in the use of solar radiation in drying of farm products and similar materials.

**New York University, Solar Energy Laboratory.** University Heights, New York 53, N.Y.

Maria Telkes.

As part of project sponsored by U.S. Office of Saline Water, designed, built, and tested flat tilted stills that were operated at the seashore with salt water. These stills avoid the formation of hard crusts from insoluble salts. A small ten-stage multiple-effect atmospheric still developed which produces 6 times more distillate than that with a single effect. Designing and building a large still of the same type, and investigating the effect of increasing the number of stages. Began study to prepare solar energy transmitting and heating insulating structures for use in buildings and solar heat collectors, under sponsorship of Dow Chemical. The collectors must be protected against heat loss by use of a structure that transmits the maximum amount of solar radiation. Prepared cellular structures using inexpensive materials and methods.

**Purdue University, Agricultural Engineering Dept.** Lafayette, Ind.

G. W. Isaacs.

Used silicon solar cells as power supply for an electric fence charger during the summer of 1957. The solar cells were used to charge a storage battery which operated the fence charger at night and during periods of low insolation. Apparatus operated in 1957 cost about \$250 and is considered too expensive for practical application. Current work in increasing the efficiency of utilization of the solar cells by increasing the intensity of radiation applied to them and eliminating the flow of reverse current through the cells during periods of low insolation.

G. M. White; G. W. Isaacs.

Developing solar-powered refrigeration systems for applications which require cooling principally during periods of high insolation, e.g., livestock shelters. Designs for livestock shelters to be investigated for reducing thermal lag and thereby increasing the coincidence of maximum cooling load and maximum insolation. Both closed-cycle and open-cycle absorption refrigeration systems currently being analyzed for feasibility in this application. The ultimate objective of the project is to determine the best combination of solar collector, refrigeration cycle, and animal shelter for reducing summer heat stress on livestock.

**Radio Corporation of America, RCA Laboratories.**  
Princeton, N.J.

J. J. Loferski; P. Rappaport.

Performance of Hoffman silicon solar cells under simultaneous illumination and irradiation by various ionizing radiations observed for the purpose of estimating the useful life of such power sources in the environment of the IGY earth satellites. (For Signal Corps.)

B. Goldstein; E. L. Lind; J. J. Loferski; L. Pensak; P. Rappaport.

Theoretical study of the most promising materials for photovoltaic solar energy conversion, including GaAs, InP, and CdTe, carried out for the Signal Corps.

L. Pensak.

Studied a new high-voltage photovoltaic effect, under Signal Corps contract, in which voltages as high as 100 v per cm were obtained in CdTe films exposed to sunlight.

B. Goldstein.

Studied properties of CdTe films. The open circuit photovoltage, short circuit photocurrent, and resistance of films of CdTe showing the high-voltage photovoltaic effect were measured as functions of light intensity and temperature.

S. G. Ellis; F. Herman; E. E. Loebner; W. J. Merz; C. W. Struck; J. G. White.

Studied high photovoltages in zinc sulfide crystals.

K. G. Hernqvist; M. Kanefsky; L. S. Nergaard.

Studied the direct conversion of heat to electrical energy by means of a thermionic diode having a high-work-function cathode and a low-work-function anode. Calculations indicate that the conversion efficiency increases very rapidly with temperature; efficiencies of about 20 per cent appear to be feasible. There is a possibility that the high temperatures required might be obtained by use of solar energy.

N. E. Lindenblad; F. D. Rosi.

Investigating new materials for thermoelectric power generation, including both metallic and semiconductor junctions. Early models have given efficiencies over 6 per cent.

**Radio Corporation of America, Electron Tube Division.** Lancaster, Pa.

P. G. Herold.

Constructed 60-in. searchlight furnace with which temperatures over 2700°C have been obtained in initial work with phosphors. Furnace has automatic sun-tracking, ob-

tained with photoconductive cells used to control elevation and azimuth drive motors.

**Stanford Research Institute.** Menlo Park, Calif.

N. K. Hiester; R. B. Beyer.

Completed solar furnace, with automatic control device on heliostat for following the sun. Work to begin on determining its performance parameters.

N. K. Hiester; F. A. Halden.

Making following studies with solar furnace, under sponsorship of government research agencies: (1) measurement of the expansion of uranium dioxide on melting; (2) preparation of high-temperature single crystals; (3) high-temperature kinetics of reactions between solids and gases.

N. K. Hiester; R. K. Cohen.

Defining for study the theoretical design parameters and the operating characteristics of cylindro-parabolic concentrators.

N. K. Hiester; C. W. Marynowski.

Providing additional design information on solar candy dryer to the Howard Stark Company, which is now constructing these devices in Puerto Rico.

K. Sancier.

Planning further work on photogalvanic solar batteries.

R. Eustis.

Completed program of evaluation of SOMOR solar engine for commercial client in June, 1957.

R. J. Marcus.

Continuing work on the photolysis of water, the Hill reaction, and electron transfer spectra, all in connection with the possibility of decomposing water by photons. Also has program underway on photochemical reactions using high-flux regions in a solar furnace. (Both sponsored by government research agencies.)

**Umbroiler Company.** 510 Farmers' Union Building, Denver 2, Colo.

G.O.G. Löf; James Klein; Robert Ruehel; Phil Gorman.

Marketing umbrella-type folding solar cooker by direct mail sales and by wholesaling to dealers and retailers. The 4-ft diameter reflector is composed of metallized Mylar film, and folds into a 30 x 10 in. carrying case which includes a tripod stand and grill.

**U.S. Air Force, Missile Development Center.** Holloman Air Force Base, N.M.

Paul D. Jose; B. I. Davis.

Work on design studies for the proposed large Air Force solar furnace in New Mexico. During summer of 1957, studies made by various workers on general problems of the solar furnace. Jose continuing detailed studies of problems concerned with the immediate design. Davis will set in operation a 5-ft solar furnace in July.

**U.S. Army, Quartermaster Research & Development Center, Pioneering Research Division.** Natick, Mass.

John M. Davies; Eugene S. Cotton; Walter Zagieboylo; William P. Lynch.

Work proceeding on the large (28 x 28 ft concentrating area) Quartermaster solar furnace, which will be used as a source of thermal radiation to simulate nuclear weapons and to facilitate protection studies.

**U.S. National Bureau of Standards, Solar Furnace Laboratory.** Washington 25, D.C.

S. Zerfoss; J. J. Diamond.

The following work is in progress with the solar furnace: (1) determination of vapor pressure of  $Al_2O_3$  as a function of atmosphere, by a transpiration technique; (2) development of temperature measurement techniques; (3) development of zone-refining accessory equipment. The following work is planned: (1) experiments in high temperature electrical conductivity of refractories; (2) single crystal growing.

**U.S. Office of Saline Water.** Washington 25, D.C.

David S. Jenkins.

Sponsored the following research in solar distillation processes: (1) G.O.G. Löf — Made design studies of a roof-type deep-basin solar still. Detailed specifications for a 5000-sq ft deep-basin still prepared and bids received for its construction in 1957. Because of estimated high cost, construction not undertaken, but decided to modify the design and conduct additional studies in order to reduce costs. (2) Maria Telkes — Developing tilted-type solar still that uses a wick, and a multiple-effect still which operates at normal atmospheric pressure. (3) Bjorksten Research Laboratories — Carrying on studies of the utilization of plastics in solar stills. Developed an

envelope-type still that makes use of wick material for the evaporation surface. (4) E. I. DuPont de Nemours — Cooperating in studies of possible application of new plastic films such as Teflon which will withstand outdoor exposure. Several experimental stills have been operated by DuPont in Wilmington, Del., the most recent consisting of 2 25-ft x 20-in. bays with black polyethylene sheets on the bottom and air-supported transparent plastic film over the top.

A development program wherein prototypes of various designs of solar stills would be operated and further developed at a seashore location will be initiated.

**U.S. Weather Bureau, Office of Climatology.** Washington 25, D.C.

H. E. Landsberg.

Continuing reporting and publishing solar radiation and related data for the United States.

**Year-Round Comfort, Inc.** 11940 Ventura Blvd., Studio City, Calif.

A.L. Ottum.

Constructed solar-heated house in Benedict Canyon, near Beverly Hills, for the architect Ronald White. The collector panel consists of 300 sq ft of Revere tube-in-strip covered with Sisel glaze, located on a hillside to the south of the house. Storage is in a buried 1000-gal tank, and the radiant heating system is placed in the floor of the house.



## SOLAR ABSTRACTS

This section brings to the attention of our readers some of the important books and papers on solar energy which have been published elsewhere during the past few months. Wherever possible, authors' abstracts have been used; other abstracts are from the standard abstract journals or are by the editorial staff of the *Journal*. Photocopies of papers abstracted below may be obtained at cost (10¢ per page) by members of the Association for Applied Solar Energy, from the Association's library at Phoenix.

Baum, V. A., (ed.), *Ispol'zovanie solnechnoi znerгии*. (Solar energy utilization.) Volume I. Moscow, USSR Academy of Sciences, 1957. 248 p. Illus.

A collection of papers by Baum and his colleagues on their investigations in solar energy applications.

Contents: V. A. Baum, "Prospects for utilizing solar energy"; I. N. Yarslavtsev, "Variations in solar and diffuse radiation totals and their time distribution in Tashkent"; V. B. Veinberg, "Efficiency of radiation absorption by radiation collector from paraboloid-cylindrical and paraboloidal mirrors"; V. B. Veinberg, "Spectral characteristics of solar collectors"; B. A. Garf, M. S. Borozdena, N. B. Rekant, "Research on surface reflectivity of solar devices"; B. A. Garf, "Rotation mechanisms for following the sun"; R. R. Aparisi, V. A. Baum, and B. A. Garf, "High-power solar installations"; H. I. Markov, "Special techniques employed in making reinforced concrete solar mirrors and some data on their performance"; B. K. Kozler, F. F. Bohdanov, J. H. Kolos, H. I. Markov, "Thermodynamic study of steam-generating parabolic mirror devices"; P. M. Brdlik, "The problem of the solar refrigerator"; D. M. Shcheholev, "Space heating with solar energy"; P. M. Brdlik, "Research and calculations regarding solar water stills"; R. R. Aparisi, "Experimental installation for producing high temperature"; B. A. Garf, "Small solar cooker"; B. A. Garf and R. K. Chuneeria, "Paraboloid-cylindrical boiler, 10 gal per hour capacity, producing 40 liters of boiling water per hour"; B. V. Petyxov, "Method of calculation for solar water heater"; H. I. Markov and N. B. Rekant, "Testing solar water heaters in Tashkent during 1952-53"; H. I. Markov, "Shading coefficient of direct incidence on glass sash of collector and total solar incidence upon the collector"; S. H. Pojarkov, "Technological and economic advantages of solar devices"; A. A. Ismailova, "Possibility of applying solar energy to drying fruit and vegetables."

Bridgers, F. H.; Paxton, D. D. and Haines, R. W., "Performance of a solar heated office building." *Heat. Pip. Air Cond.* 29(11): 165-70, Nov. 1957. Illus.

The heating and cooling system of the Bridgers and Paxton office building in Albuquerque and the instrumentation for determining performance are described. Records of sunshine data for the 1956-57 heating season in Albuquerque and the heat pump operation for this period are tabulated. The cost of this heating system is compared to a conventional system. Various details of the operation, including the relation of heat pump operation to degree days and solar radiation intensity, calculated and recorded storage tank temperature, and ratio of heat supplied to auxiliary unit to the total heat requirements, are discussed. An improved design procedure is given in the appendix.

Conn, William M., "Accurate temperature measurements in work with solar furnaces." *Am. J. Physics* 24(8): 581-83, Nov. 1956. Illus.

Measurement of temperatures above 1500°C in a solar furnace is discussed. If the sample is heated without melting, the true temperature can be obtained from the brightness temperature, determined with an optical pyrometer or phototube. If the sample is studied at or above the melting range, it is necessary to separate the radiation emitted by the sample from the incident or reflected radiation while the temperature is measured. This was accomplished by shutting off the incident radiation with a high-speed rotating shutter or sector.

Duwez, Pol and Loh, Eugene, "Phase relationships in the system zirconia-thoria." *J. Am. Ceram. Soc.* 40(9): 321-24, Sept. 1957. Illus.

The phase relationships in the system zirconia-thoria were investigated by X-ray diffraction and dilatometric methods. The specimens were melted in air at the focus of a solar furnace. The existence of a cubic calcium fluoride-type solid solution was established for thoria concentrations above 17.5 mole per cent. However, this solid solution is stable only at high temperature, and, after prolonged heating at 2000°C and at 1350°C, it decomposes into tetragonal zirconia (which during subsequent cooling undergoes the unavoidable tetragonal-monoclinic inversion) and a thoria-rich phase containing at least 99 mole per cent thoria. (author's abst.)

Hiester, Nevin K.; Tietz, Thomas E. and Loh, Eugene, "Theoretical considerations on performance characteristics of solar furnaces." *Jet Propulsion* May 1957: 507-12, 546. Illus.

The theoretical factors affecting the performance of the paraboloid-type solar furnace are discussed. Calculations of the heat flux and the maximum temperature obtainable at the focus are presented for furnaces of different diameter-to-focal-length ratios. The analysis is extended to the California Institute of Technology lens-type furnace. The results indicate that a paraboloid of relatively low quality is capable of achieving temperatures over 2000°K. On the other hand, a research furnace capable of attaining temperatures in the range of 3600° to 4200°K would have to have a paraboloid of very high quality. (authors' abst.)

Jordan, R. C., "The place of the heat pump and solar energy in space conditioning." *Proc. Am. Power Conf.* 39: 369-79, 1957. Illus.

The current status of heat pump applications in the United States is outlined, and the possibilities of utilizing solar energy in space-heating installations are considered, with a table summarizing design conditions and operating costs for heat pump, solar heat source system. Two recent unusual space-heating installations are described: the Southdale regional shopping center, which contains the world's largest heat pump installation; and the Bridgers and Paxton solar-heated building in Albuquerque, which combines a heat pump with a direct solar heating system.

Nevins, R. G. and McNall, P. E., "A high-flux low-temperature solar collector." *Heat. Pip. Air Cond.* 29(11): 171-76, Nov. 1957. Illus.

Solar collection efficiencies of 65 and 75 per cent were ob-

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tained on clear days during the summer of 1956 with a focusing low-temperature solar collector. A 5-ft diameter surplus searchlight mirror was used to focus the solar energy on a 6-in. diameter collector mounted near the focus of the mirror. Solar energy was collected at a rate of 3700 to 4200 Btu per hour at collector temperatures of 100° to 170°F. Collection efficiencies on cloudy days varied from 40 to 60 per cent based on the available direct radiation and from 30 to 45 per cent based on the available total radiation.

Theoretical analysis is presented to show the effect of the concentrating power,  $P$ , on the collection efficiency where  $P$  is the ratio of the area of intercepted radiation to the area of the collector surface. It is found that for values of  $P$  greater than 15, no glass cover plates should be used if the transmissivity of the glass was 0.91 or less. The effect of ambient air temperature on the collection efficiency is also shown.

A discussion of a blackbody cover to increase the effective absorptivity of the collector is presented. Theoretical calculations show that collection efficiencies can be increased with use of the cover. The effect of cover emissivity was found to be small if the cover is insulated. For an uninsulated cover the efficiency decreases with increasing cover emissivity. (authors' abst.)

Oshida, Isao, *Solar energy*. Tokyo, Nikkan Kōgyō Shinbun Sha, 1958. 296 + 31 p. Illus. (In Japanese.)

A discussion of the increasingly serious problem of our energy shortage and of the possibilities for utilizing solar energy to overcome it, drawing on literature references up to 1958. Following an explanation and criticism of all methods of utilizing solar energy hitherto proposed, the author concludes that the most promising is the conversion of solar energy directly to chemical energy, because the latter is convenient to store and to transform to electric energy. Some of the problems which must be met in this field are outlined. The book concludes with a comprehensive bibliography of literature references, chiefly from U.S. sources.

Réménieras, G., "Etude de l'utilisation de l'énergie pour la production d'énergie électrique." (Study of the utilization of solar energy for the production of electrical energy.) *Rev. Gén. Elec.* 66:593-626, Dec. 1957. Illus.

The first section of this paper deals with the amount of solar energy available on various surfaces at different localities. Various methods of transforming solar radiation into electrical energy are then outlined. These can be grouped in two classes: indirect methods, in which the radiation is first transformed into heat by absorption by a collector, and direct methods, in which light energy is transformed into electric energy, as in thermocouples or photovoltaic cells. Various types of flat-plate collectors are discussed, together with the different types of heat loss, and several tests by G. T. Ward are summarized. Concentrating collectors are also considered in detail, and several actual examples given, including the Montlouis solar furnace and the USSR power station at Mount Ararat. Heat engines for flat-plate and concentrating collectors are discussed. Various types of thermoelectric generators and photoelectric cells are considered, including the Bell solar battery. The third section is a survey of the economic problem, in which the price of solar energy is compared to that of conventional power sources.

Sapsford, C. M., "An estimation of solar energy radiation for Australia." *Austral. J. Sci.* 20(4):99-105, Nov. 1957. Illus.

The fundamental importance of obtaining accurate solar radiation records for a number of stations on the Australian continent is stressed while an approximate method of estimating average daily solar radiation (sun and sky) is outlined, the calculations being based upon published figures. The limitations of this method are stressed, and a recommendation is made for interested organizations and government bodies to collaborate in providing facilities for an extensive network of solar radiation recording stations. A start has been made in this direction by the Meteorological Department of Melbourne University and the New South Wales University of Technology. It is, however, noted that some calculation would always be necessary to fill in the solar radiation values between points where records were available. (author's abst.)

Trombe, Félix and Foëx, Marc, "Préparation de monocristaux au moyen de fours centrifuges chauffés par le rayonnement solaire." (Preparation of monocrystals by means of a centrifugal solar furnace.) *Compt. Rend.* 244:2605-7, May 20, 1957. Illus.

A centrifugal solar furnace is described, in which it has been possible to obtain monocrystal formations in the central zone. This method has been applied to the production of  $Al_2O_3 \cdot MgO$  by means of the 75 kw solar furnace at Montlouis.

———"Traitement par le rayonnement solaire de substances réfractaires placées sur plaques métalliques réfrigérées." (Treatment by solar radiation of refractory substances placed on refrigerated metallic plates.) *Bull. Soc. Chim. France* 1957: 532-34. Illus.

An apparatus is described for the treatment at high temperatures of various substances by the concentration of radiation. The heated product is placed on a refrigerated metallic plate, in order to avoid contamination of the substance by its support. It is also possible to place over the apparatus a bell or sphere of glass in order to work in a conditioned atmosphere or to gather the gases given off by the reaction. This apparatus can be used to break down various refractory oxides in order to analyze them, a problem which is often difficult to solve by ordinary procedures. In numerous cases,  $CaO$  is used on a solid mass. Several other types of application are described, in particular the preparation of certain pure substances of well-defined composition. (authors' abst.)

Wilson, B. W., "Report on field tests of solar energy absorbers for drying vine fruit carried out in co-operation with the Commonwealth Research Station, Merbein, Vic., Feb.-Mar. 1957." Commonwealth Scientific and Industrial Research Organization, Division of Industrial Chemistry, June 1957. 22 p. Illus.

Field tests on two types of solar energy absorbers for drying fruit, one based on a solar still design and the other related to normal air drying with the air temperature increased by a solar energy absorber, were carried out during the 1957 harvest. This report describes the design and construction of the solar absorbers and reviews the results of the tests under field conditions.

## COMMENTS ON PAPERS

Beginning with this issue, *Solar Energy* will present, in this section, letters, comments, and discussion of papers which have appeared in earlier issues. Journal readers are therefore invited to submit their remarks on any of the papers published to date, or on information in the "Solar Abstracts" or "World Research Activities" sections, to the attention of the editor.

Sir:

I read with great interest the paper entitled "Plastics for Focusing Collectors" in the October issue of your Journal. The problem of solar cooking is an important one here, especially in native cities which have grown up near European centers.

I should like to point out that, according to information from E. I. duPont de Nemours, "ordinary Mylar polyester film is not recommended for outdoor use as it degrades under certain conditions of exposure." This company is also "in the process of developing a weather-

able modification of Mylar, but this material is not yet available in commercial quantities." It would thus seem preferable not to use the present Mylar in the manufacture of solar cookers.

I would also like to draw attention to the fact that one very large item in the price of a solar cooker is likely to be the transportation cost. This factor doubled, for instance, the price of two Indian solar cookers between Calcutta and Bukavu (Belgian Congo). As this cost depends largely on the bulk of the merchandise, it might well be that a durable folding-type solar cooker would for a long time be preferable to a rigid one, even though rigid ones could eventually be stacked into one another for shipping once they are mass-produced and available in large quantities.

Reference: *Fol. Scient. Afr. Cent.* 2(2):16, 1956.

J. CL. DE BREMAECKER  
*Institut pour la Recherche  
Scientifique en Afrique  
Centrale  
Belgian Congo*

## ERRATA & ADDENDA

"Concentration of the solar radiation in a solar furnace," by Taro Hisada *et al.*, in Vol. I, No. 4, Oct. 1957: Fig. 7 and Fig. 8, captions should be transposed; p. 14, col. 1 (abstract), for "300 watts per cm" read "300 watts per sq cm"; p. 17, col. 1, for "specimens of 30 mm" read

"specimens of 30 mm in diameter."

"Computation of absorber area," by J. Cl. de Bremaecker, in Vol. II, No. 2, Jan. 1958: p. 36, col. 1 (abstract), for "\$81" read "\$5."

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